



Diagnosis and Fault-tolerant Control, 3rd Edition

Blanke, Mogens; Kinnaert, Michel; Lunze, Jan; Staroswiecki, Marcel

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Mogens Blanke · Michel Kinnaert
Jan Lunze · Marcel Staroswiecki

Diagnosis and Fault-Tolerant Control

Third Edition

 Springer

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Mogens Blanke · Michel Kinnaert
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Diagnosis and Fault-Tolerant Control

Third Edition

With 218 Figures, 129 Examples, and 43 Exercises

 Springer

Mogens Blanke
Department of Electrical Engineering,
Automation and Control Group
Technical University of Denmark
Kongens Lyngby
Denmark

Michel Kinnaert
Service d'Automatique et d'Analyse des
Systèmes
Université Libre de Bruxelles
Brussels
Belgium

Jan Lunze
Ruhr-Universität Bochum
Bochum
Germany

Marcel Staroswiecki
Ecole Polytechnique Universitaire de Lille
Université Lille I
Villeneuve d'Ascq cedex
France

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Preface

Technological systems are vulnerable to faults. Actuator faults reduce the performance of control systems and may even cause a complete breakdown of the system. Erroneous sensor readings are the reason for operating points that are far from the optimal ones. Wear reduces the efficiency and quality of a production line. In many fault situations, the system operation has to be stopped to avoid damage to machinery and humans.

As a consequence, the detection and the handling of faults play an increasing role in modern technology, where many highly automated components interact in a complex way such that a fault in a single component may cause the malfunction of the whole system. Due to the simultaneously increasing economic demands and the numerous ecological and safety requirements to be met, high dependability of technological systems has become a dominant goal in industry.

This book introduces the main ideas of fault diagnosis and fault-tolerant control. It gives a thorough survey of new methods that have been developed in the recent years and demonstrates them with examples. To the knowledge of the authors, all major aspects of fault-tolerant control are treated for the first time in a single book from a common viewpoint.

Scope. Whereas fault diagnosis has been the subject of intensive research since the 1970s and there are several good books on this subject, systematic methods for fault handling is a new area of automatic control. The book considers both steps of fault-tolerant control together and shows how the information gained by model-based diagnosis can be used to find remedial actions that adapt the control algorithms to the faulty conditions in order to keep a system in operation. Basically, such actions can be classified as *fault accommodation*, which deals with the autonomous adaptation of the controller parameters to the faulty plant behaviour, and *control reconfiguration*, which includes the selection of a new control configuration and the online re-design of the controller.

The solution of these problems includes new analysis tasks like the test of the reconfigurability of the plant or the search for redundant sensors and actuators, which can replace faulty components. The aim is to close the control loop after a

breakdown of a component in the control loop has brought the controller out of operation. With respect to fault accommodation and control reconfiguration, the book presents the current state of the art.

The fault diagnostic parts of the book describe those methods and ideas which can be used to identify the fault with sufficient detail for fault accommodation or reconfiguration. The detection of a fault alone is not sufficient for fault-tolerant control, because the fault location and, possibly, the fault magnitude have to be known to activate appropriate remedial actions.

The design and implementation of fault-tolerant control necessitates a variety of techniques. The search for redundancies concerning the information and the possible control activities in a system, the selection of a reasonable control configuration, and the combination of diagnostic methods with controller design methods are some of the problems to be tackled. This set of different tasks cannot be dealt with by a single analytical model of the system under consideration, but different viewpoints have to be combined. For this reason, the book introduces a variety of models of dynamical systems and describes how these models can be used in fault-tolerant control. A component-oriented description of the system architecture is used to find the cause-effect chains from the primary faults towards the measured fault symptoms. A structural analysis based on bi-partite structure graphs is introduced to elaborate the analytical redundancies that can be used for fault diagnosis and fault-tolerant control actions. For the well-known continuous system representations like the state-space model and the transfer function, diagnostic methods and their extensions to fault-tolerant control are explained. With the presentation of diagnostic and reconfiguration methods for discrete-event systems, the book provides further novel material that has not yet been described in monographs or textbooks.

Structure of the book. This monograph consists of three parts:

- **Part I: Analysis based on components and system structure.** It is shown how abstract models of dynamical systems like component-oriented representations or structural graphs can be used to identify the connections between faults and symptoms and to find analytic redundancy relations for diagnosing faults.
- **Part II: Continuous systems.** Method for fault detection, fault identification and the re-design of the controller for a faulty system are described for continuous-variable systems that are represented by differential equations, difference equations or state-space models.
- **Part III: Discrete-event systems.** Methods for fault diagnosis and control reconfiguration are presented for discrete-event systems, whose behaviour is characterised by sequences of discrete signal changes and represented by deterministic, nondeterministic or stochastic automata.

As each of the models used requires its own mathematical background and the methods based on these models follow different lines of thinking, the book cannot present the methods in all details. The aim is to give the readers a broad view of the field and provide them with bibliographical notes for further reading. A further

reason for the different depth with which the chapters tackle the fault-tolerant control problems is given by the current status of research. Whereas for continuous-variable systems, fault diagnostic and fault-tolerant control methods have been developed for long, discrete-event systems became the subject of substantial research with respect to the topic of this book not before the 1990s. Hence, this field has not yet reached the same maturity as fault-tolerant control of continuous systems.

Many of the ideas are illustrated by **two running examples** that concern a simple tank system and a ship autopilot. The common use of these examples in several chapters makes a comparison of the alternative approaches very easy. It is the knowledge of the aims, models, ideas and methods used for different problems of fault diagnosis and fault-tolerant control that enables a control engineer to tackle practical problems under the circumstances given by the particular field of application. To introduce him to this knowledge is the primary aim of this book.

Level of the book. The intended readers of the book are graduate students of control, electrical, mechanical or process engineering with knowledge in dynamical systems, control design and filtering. The authors use the text in regular courses at the Université Libre de Bruxelles, the Ruhr-Universität Bochum, the Technical University of Denmark and the Norwegian University of Science and Technology.

In the introductory parts of all chapters the problems to be solved are posed in a framework that is familiar to practising engineers. They describe the new ideas and concepts of fault diagnosis and fault-tolerant control in an intuitive way, before these ideas are brought into a strict mathematical form. Examples illustrate the applicability of the methods. Bibliographical notes at the end of each chapter point to the origins of the presented ideas and the current research lines. The evaluation of the methods and the application studies should help the readers to assess the available methods and the limits of the present knowledge about fault-tolerant control with respect to their particular field of application.

The book is self-contained with a review of some basics in the appendices. Many figures illustrate the problems, methods and results in an intuitive way and make the interpretation of the rigorous mathematical treatment easier.

Common research. The large scope of the book was made possible by the close cooperation and by the common research of the four authors together with their Ph.D. students and colleagues. The introductory part (Chaps. 1 through 3) describe common ideas and results. The presentation of the methods for dealing with the system architecture (Chap. 4) is common work of the groups of Mogens Blanke in Aalborg and Lyngby (Denmark) and Marcel Staroswiecki in Lille (France). The part on structural analysis (Chap. 5) introduces the methods developed in Lille as they have been extended later on in Bochum and Lyngby. Diagnostic methods for continuous systems have been elaborated by many groups. The presentation of these ideas that can be used in fault-tolerant control (Chaps. 6 and 7) resulted from the common work and teaching experiences of Mogens Blanke, Michel Kinnaert (Brussels, Belgium) and Marcel Staroswiecki. Chapters 8–10 on fault

accommodation and control reconfiguration describe ideas of the four authors. The methods for dealing with discrete-event systems (Chaps. 11 and 12) have been elaborated by the group of Jan Lunze in Hamburg and Bochum (Germany).

Industrial applications. The methodologies presented in this book have been used in numerous industrial applications, among others in the automotive industry (fault-tolerant steering-by-wire, air system diagnosis), for aerospace (fault diagnosis of autonomous aircraft, fault-tolerant control of the Danish Ørsted satellite, detection of control surface vibrations, monitoring of the engine lubrication system), in the marine industry (fault-tolerant sensor fusion for navigation and for position mooring control), in offshore industry (prognosis and diagnosis of down-hole-drilling incidents), for wind turbines (pitch, load and yaw systems fault diagnosis, diagnosis of generator cooling), for electrical drives and in the process industry. The experiences gained by these applications are reflected in the selection and presentation of the material of this book.

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Third edition. After this book was used for a decade by several research groups, the third edition resulted from a major rewriting and restructuring of the material. In particular, Chap. 5 on structural analysis has been rewritten with more emphasis on the algorithms for finding analytical redundancy relations and the relation between structural and numerical properties of dynamical systems. Chapter 7 now includes more material on statistical change detection and isolation. In Chaps. 8 and 9, the reconfigurability analysis is presented separately from fault accommodation and reconfiguration methods and new methods have been inserted to extend this part towards the state of the art. Distributed diagnosis and distributed fault-tolerant

control have been included as a new topic for both continuous and discrete-event systems in Chaps. 10 and 12, respectively. Chapters 11 and 12 have been completely rewritten. The application chapter of the former editions has been moved to the book website.

Several new exercises should stimulate the readers to apply the methods presented to simple examples. The bibliographical notes have been updated and extended.¹

Kongens Lyngby
Brussels
Bochum
Paris
May 2015

Mogens Blanke
Michel Kinnaert
Jan Lunze
Marcel Staroswiecki

¹The book homepage at www.atp.rub.de/n/buch/ftcbook provides supplementary material for this book including lecture slides. A solutions manual can be made available for lecturers.

Contents

1	Introduction to Diagnosis and Fault-Tolerant Control	1
1.1	Technological Processes Subject to Faults	1
1.2	Faults and Fault Tolerance	3
1.2.1	Faults	3
1.2.2	Requirements and Properties of Systems Subject to Faults	8
1.3	Elements of Fault-Tolerant Control	10
1.3.1	Structure of Fault-Tolerant Control Systems	10
1.3.2	Main Ideas of Fault Diagnosis	13
1.3.3	Main Ideas of Controller Redesign	18
1.3.4	A Practical View on Fault-Tolerant Control	22
1.4	Architecture of Fault-Tolerant Control	23
1.4.1	Architectural Options.	23
1.4.2	Distributed Systems.	24
1.4.3	Remote Control and Diagnosis	27
1.5	Survey of the Book.	31
1.6	Bibliographical Notes	34
2	Examples	37
2.1	Two-Tank System.	37
2.2	Three-Tank System	41
2.3	Ship Steering and Track Control.	45

Part I Analysis Based on Components and System Structure

3	Models of Dynamical Systems	53
3.1	Fundamental Notions.	53
3.2	Modelling the System Architecture	57
3.3	System Behaviour - Basic Modelling Features	59
3.4	Continuous-Variable Systems	61

3.5	System Structure	65
3.6	Discrete-Event Systems	67
3.7	Hybrid Systems	70
3.8	Links Between the Different Models	72
3.9	Exercises	74
3.10	Bibliographical Notes	77
4	Analysis Based on Components and Architecture	79
4.1	Introduction	79
4.2	Faults in Components and Their Consequences.	81
4.3	Fault Propagation Analysis.	82
4.4	Graph Representation of Component Architecture	92
4.5	Fault Propagation with a Closed Loop.	94
4.5.1	Cutting the Closed Fault Propagation Loop	95
4.5.2	Assessment of the Severity of the Fault Effects.	97
4.5.3	Decision About Fault Handling.	97
4.6	Generic Component Models	97
4.6.1	Services	98
4.6.2	Introduction of the Generic Component Model	100
4.6.3	Simple Components	101
4.6.4	Complex Components	103
4.6.5	Building Systems from Components	106
4.7	Fault-Tolerance Analysis	108
4.7.1	Relation Between Services and Objectives	109
4.7.2	Management of Service Versions	111
4.7.3	Management of Operation Modes	113
4.8	Exercises	114
4.9	Bibliographical Notes	117
5	Structural Analysis	119
5.1	Introduction	119
5.2	Structural Model	121
5.2.1	Structure as a Bipartite Graph.	121
5.2.2	Subsystems	127
5.2.3	Structural Properties	129
5.2.4	Known and Unknown Variables	132
5.3	Matching in Bipartite Graphs	134
5.3.1	Definitions	135
5.3.2	Oriented Graph Associated with a Matching.	138
5.3.3	Causal Interpretation of Oriented Structure Graphs	141
5.4	Structural Decomposition of Systems.	149
5.4.1	Canonical Subsystems	149
5.4.2	Interpretation of the Canonical Decomposition	156

5.5	Matching Algorithms	161
5.5.1	Ranking Algorithm	161
5.5.2	General Matching Algorithm	165
5.5.3	Maximum Flow Algorithm	168
5.5.4	Minimal Over-Determined Subsystems Approach	171
5.6	Structural Diagnosability and Isolability	173
5.6.1	Analytical Redundancy-Based Fault Detection and Isolation	174
5.6.2	Structurally Monitorable Subsystems	177
5.6.3	Finding Analytic Redundancy Relations	179
5.6.4	Structural Detectability and Isolability	181
5.6.5	Design of Robust and Structured Residuals	184
5.6.6	Active Fault Isolation	192
5.7	Structural Controllability and Structural Observability	196
5.7.1	Observability and Computability	196
5.7.2	Structural Observability Conditions	197
5.7.3	Observability and Structural Observability of Linear Systems	199
5.7.4	Graph-Based Interpretation and Formal Computation	201
5.7.5	Structural Controllability	202
5.8	Structural Analysis in Summary	205
5.9	Exercises	207
5.10	Bibliographical Notes	211

Part II Continuous-Variable Systems

6	Fault Diagnosis of Deterministic Systems	215
6.1	Introduction	215
6.2	Analytical Redundancy in Nonlinear Deterministic Systems	218
6.2.1	Logical Background	218
6.2.2	Analytical Redundancy Relations with No Unknown Inputs	219
6.2.3	Unknown Inputs, Exact Decoupling	222
6.2.4	How to Find Analytical Redundancy Relations	223
6.2.5	ARR-based Diagnosis	223
6.3	Analytical Redundancy Relations for Linear Deterministic Systems - Time Domain	226
6.4	Analytical Redundancy Relations for Linear Deterministic Systems - Frequency Domain	231
6.4.1	Fault Detection	231
6.4.2	Solution by the Parity Space Approach	232

6.4.3	Fault Isolation.	241
6.4.4	Fault Estimation	244
6.5	Optimisation-Based Approach to Diagnosis	248
6.5.1	Problem Statement	248
6.5.2	Solution Using the Standard Setup Formulation	252
6.5.3	Residual Generation	255
6.6	Residual Evaluation.	261
6.6.1	Residual - General Case.	261
6.6.2	Evaluation Against a Threshold	263
6.7	Exercises	268
6.8	Bibliographical Notes	273
7	Fault Diagnosis of Stochastic Systems	275
7.1	Introduction	275
7.2	Change Detection Algorithms.	276
7.2.1	Sequential Change Detection: The Scalar Case	276
7.2.2	Detection of a <i>Known</i> Change - The CUSUM Algorithm	278
7.2.3	Detection Properties for the CUSUM Algorithm	283
7.2.4	Detection of an <i>Unknown</i> Change - The Generalised Likelihood Ratio Algorithm	288
7.2.5	Sequential Change Detection: The Vector Case.	296
7.2.6	Sequential Change Detection and Isolation: The Vector Case	306
7.3	Kalman Filter Approach to Diagnosis	311
7.3.1	Model	311
7.3.2	Fault Detection	312
7.3.3	Fault Estimation	331
7.3.4	Fault Isolation.	333
7.4	Exercises	338
7.5	Bibliographical Notes	341
8	Reconfigurability Analysis.	343
8.1	The Fault-Tolerant Control Problem	343
8.1.1	Standard Control Problem	343
8.1.2	Impacts of Faults on the Control Problem	345
8.1.3	Passive Versus Active Fault-Tolerant Control	347
8.1.4	Available Knowledge	348
8.1.5	Active Fault-Tolerant Control Strategies.	349
8.1.6	Supervision	350
8.2	Fault-Tolerant Control Architecture	351
8.3	Fault-Tolerant Linear Quadratic Design	354
8.3.1	Control Problem	354
8.3.2	Control of the Nominal Plant	354

8.3.3	Fault Tolerance with Respect to Actuator Faults	356
8.3.4	Fault Accommodation	358
8.3.5	Control Reconfiguration.	362
8.4	The Lattice of Actuator Subsets	362
8.4.1	Actuator Configurations	363
8.4.2	Critical Actuator Subsets and Minimal Recoverable Configurations	366
8.5	Implementational Issues of Fault-Tolerant Control.	367
8.5.1	On-Line Re-design Versus Bank of Control Laws	367
8.5.2	The Passive–Active Approach.	367
8.5.3	Reducing the Reliability Over-Cost	373
8.6	Fault-Tolerance Evaluation.	377
8.6.1	Deterministic Measures	377
8.6.2	Probabilistic Measures	378
8.6.3	Sensitivity	379
8.7	Exercises	382
8.8	Bibliographical Notes	386
9	Fault Accommodation and Reconfiguration Methods	389
9.1	Fault-Tolerant Model-Matching Design	389
9.1.1	Reconfiguration Problem	389
9.1.2	Pseudo-Inverse Method	391
9.1.3	Model-Matching Control for Sensor Failures	393
9.1.4	Model-Matching Control for Actuator Failures	394
9.1.5	Markov Parameter Approach to Control Reconfiguration for Actuator Failures	398
9.2	Control Reconfiguration for Actuator or Sensor Failures	402
9.2.1	The Idea of Virtual Sensors and Virtual Actuators.	402
9.2.2	Reconfiguration Problem	404
9.2.3	Virtual Sensor.	406
9.2.4	Virtual Actuator	410
9.2.5	Duality Between Virtual Sensors and Virtual Actuators.	421
9.2.6	Experimental Evaluation: Level and Temperature Control	421
9.2.7	Experimental Evaluation: Conductivity Control Loop	427
9.3	Fault Recovery by Nominal Trajectory Tracking.	436
9.3.1	Problem Setting	437
9.3.2	Solution.	439
9.4	Fault-Tolerant \mathcal{H}_∞ Design	446
9.4.1	System Description	447
9.4.2	Youla-Kucera Parameterisation in Coprime Factorisation Form	448

9.4.3	Parametrisation in the State-Space Form.	451
9.4.4	Simultaneous Design of the Controller and the Residual Generator.	453
9.5	Handling the Fault Recovery Transients.	456
9.5.1	Switching Between Controllers	456
9.5.2	Progressive Fault Accommodation.	458
9.6	Exercises	463
9.7	Bibliographical Notes	465
10	Distributed Fault Diagnosis and Fault-Tolerant Control	467
10.1	Introduction	467
10.2	Distributed Systems.	468
10.2.1	System Decomposition.	468
10.2.2	Distributed Control	472
10.2.3	Distributed Diagnosis	474
10.2.4	Communication Cost	474
10.2.5	Communication Schemes	474
10.3	Distributed Diagnosis Design	476
10.3.1	Structural Diagnoser	476
10.3.2	Logical Theory of Diagnosis	477
10.3.3	Practical Diagnoser and Real-Time Operation	481
10.3.4	Local Diagnosers and Their Coordination.	482
10.3.5	Distribution Schemes.	488
10.4	Design of the Local Diagnosers	490
10.4.1	Specifications	490
10.4.2	Simple Distribution Problem.	490
10.4.3	Distribution Under Computing Cost Constraints	493
10.4.4	The Bilateral Agreements Scheme	496
10.4.5	Fault-Tolerant Distributed Diagnosis	499
10.5	Fault-Tolerant Control by Information Pattern Reconfiguration	499
10.5.1	Admissibility and Reconfigurability.	500
10.5.2	Information Pattern Reconfiguration	503
10.5.3	Publisher/Subscriber Scheme	506
10.5.4	Bilateral Communication Scheme	507
10.5.5	Extensions	511
10.5.6	Minimal Reconfiguration Effort	512
10.6	Exercises	514
10.7	Bibliographical Notes	517

Part III Discrete-Event Systems

11	Fault Diagnosis of Discrete-Event Systems	521
11.1	Overview of Part III	521
11.2	Models of Discrete-Event Systems	524
11.2.1	Deterministic and Nondeterministic Systems.	524
11.2.2	Deterministic Automata	527
11.2.3	Nondeterministic Automata	529
11.2.4	Stochastic Automata	531
11.2.5	Model of the Faulty System	538
11.3	Diagnostic Problems and Ways of Solution	543
11.4	Diagnosis of Deterministic Automata.	548
11.4.1	Diagnostic Algorithm	548
11.4.2	Results on Deterministic Automata with Equivalent States	549
11.4.3	Fault Detectability.	555
11.4.4	Fault Identifiability	557
11.4.5	Method for Determining Distinguishing Input Sequences	560
11.5	Diagnosis of Nondeterministic Automata	567
11.5.1	Method for Testing the Consistency of an I/O Pair with a Nondeterministic Automaton.	567
11.5.2	Diagnostic Algorithm	571
11.6	State Observation of Stochastic Automata	574
11.6.1	Method for Testing the Consistency of an I/O Pair with a Stochastic Automaton	575
11.6.2	Observation Algorithm.	583
11.6.3	Observability of Stochastic Automata	584
11.6.4	Distinguishing Inputs.	589
11.7	Diagnosis of Stochastic Automata	592
11.7.1	Principle of Consistency-Based Diagnosis Applied to Stochastic Automata	592
11.7.2	Diagnosis of Stochastic Automata with Constant Faults	593
11.7.3	Extension to Time-Varying Faults	597
11.7.4	Diagnosability of Stochastic Automata.	598
11.8	Exercises	602
11.9	Bibliographical Notes	603
12	Diagnosis of I/O Automata Networks	607
12.1	Centralised Versus Decentralised Diagnosis of Discrete-Event Systems	607
12.2	Representation of Complex Systems by I/O Automata Networks	610

12.2.1	Composite Systems to Be Diagnosed	610
12.2.2	Model of the Overall System	612
12.3	Decentralised Consistency Test	616
12.3.1	Consistency Test for the Overall System	616
12.3.2	Consistency Test for the Subsystems	617
12.3.3	State Observation Result	620
12.4	Centralised Versus Decentralised Diagnosis	620
12.4.1	Completeness of the Diagnostic Result	620
12.4.2	Centralised Diagnosis	621
12.4.3	Decentralised Diagnosis	622
12.5	System Properties and Simplification of Diagnosis	623
12.5.1	Aim of Analysis	623
12.5.2	Autonomy of Subsystems	623
12.5.3	Asynchronous State Transitions	627
12.5.4	Extensions	636
12.6	Exercises	637
12.7	Bibliographical Notes	639
Appendix A: Some Prerequisites on Vectors and Matrices		641
Appendix B: Notions of Probability Theory		645
Appendix C: Nomenclature		659
Appendix D: Terminology		661
Appendix E: Dictionary		667
References		671
Index		689