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Third Edition

Springer

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Diagnosis and Fault-Tolerant Control

Third Edition

With 218 Figures, 129 Examples, and 43 Exercises

Springer

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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]

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May 2015

[1]The 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.

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Part III Discrete-Event Systems