Chapter 1
Introduction

1.1 Linear Synthesis Techniques for Fault Diagnosis

Fault diagnosis is a widely used term across many application domains. In this book we restrict the meaning of this term to designate the usage of specific techniques to discover anomalous behaviours occurring in physical plants (known as *fault detection*) and the more challenging aspect of locating a fault within an industrial equipment (known as *fault isolation*). The subsequent characterization of the type, size and nature of occurred faults (known as *fault identification*) is also often a part of fault diagnosis. Among many approaches for fault diagnosis we focus on the model-based framework, where plant models are used to provide the required redundancy, also called *analytical redundancy*, to execute the fault detection and isolation tasks. A further restriction we purposely made is to restrict our focus to the class of *linear time-invariant* (LTI) plant models, for which a reasonably complete theory for the synthesis of *fault detection and isolation* (FDI) filters exists.

The focus on linear system techniques may appear as a strong limitation, taking into account that most technical processes are nonlinear systems and their dynamical behaviour depends on parameters, which may vary during the plant operation or may have uncertain values. Besides that, unknown external signals, acting as physical disturbances (e.g., external loads) as well as the ubiquitous presence of measurement noises, often increase the complexity of problem solving. To account (to some extent) for these inherent modelling deficiencies, linear models depending on parameters, the so-called *linear parameter-varying* (LPV) models, or collections of linearized models, the so-called LTI *multiple models*, can be used to serve as approximate plant models. These models can then be put in a standard form which underlies all developments in this book.

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The main emphasis of the book is on procedural aspects, by presenting general synthesis procedures of FDI filters to address six “canonical” problems, termed as fault detection, fault isolation and reference model-matching problems, aiming for both exact and approximate solutions. The main goal of the book is to provide a comprehensive presentation of the synthesis algorithms for the formulated problems, both at a conceptual level (using frequency-domain concepts) as well as at a detailed implementable algorithm level (using state-space description based computational methods). Although the discussion of procedural aspects is a recurring theme in several textbooks, in our opinion this is the first time that a complete collection of numerically viable methods are described, which can serve as basis for robust numerical software implementations. Most of the “computational” methods described in the fault diagnosis literature are not adequate for this purpose. The reasons are simple: the basic requirements for satisfactory numerical algorithms (for example, as those to solve linear algebra problems) are not fulfilled. Most of time, the important aspect of numerical reliability is completely ignored, and therefore many computational algorithms are provably numerically unstable. Also, the use of ill-conditioned coordinate transformations (e.g., to compute certain canonical forms), may drastically worsen the conditioning of the problem, by increasing the sensitivity of solution to variations in problem data. Thus, the effects of inherent roundoff errors are amplified and the accuracy of the solution is diminished.

We also present the somewhat new topic of the model detection, which consists of finding in a collection of available models that one which best matches the current plant behaviour. The solution of this problem is highly relevant to solving special classes of fault detection problems (e.g., as those due to extreme variations of plant parameters) or in the multiple-model-based adaptive control approaches.

An important novelty of this book is the many computational examples intended for the use within the popular MATLAB environment. The underlying computational tools are either part of MATLAB itself, or are free software developed by the author as part of this book project. All synthesis procedures are accompanied by synthesis examples, for which MATLAB scripts are included in the book. These scripts can be seen as prototype implementations of the synthesis procedures and can serve as starting points for production quality implementations of dedicated FDI filter synthesis tools. All software tools, including the scripts associated to the worked out examples and case studies, are freely available (see the author’s homepage dedicated to this book project[1]).

To a lesser extent we addressed the decision-making aspects, which are however crucial for the use of fault diagnosis systems. The presented norm-based decision schemes can be easily replaced by statistical methods based on change detection techniques.

There are several issues which are not included in the presentation, for example, synthesis methods based on the parity-space approach, polynomial representation or unknown-input observers. The reasons for this are either the lack of the generality

[1] https://sites.google.com/view/andreasvarga/home/book.

of an approach (e.g., the observer-based method) or the intrinsic numerical instability of the associated computations (e.g., parity-space and polynomial approaches). Furthermore, we exclusively use a deterministic framework, thus leaving out a rich collection of statistical approaches. Note however, that the synthesis approaches described in the book may prove useful also for a stochastic framework, since the main difference lies in the employed decision-making tools (i.e., statistical methods instead of norm-based approaches).

1.2 Outline of the Book

The book naturally falls into two parts, while a third part contains extensive background material. We briefly comment on the contents of these parts.

Part I – Basics of Fault Diagnosis. This part contains four chapters, which serve to introduce the fault diagnosis topic and to formulate the basic synthesis problems associated with it. Chapter 1 is introductory. Chapter 2 introduces the standard forms of LTI models used throughout the book for the synthesis of fault detection filters. Both input–output and state-space representations are used, where the former mainly serves to simplify the problem formulations and describe conceptual synthesis procedures, while the latter serves for developing reliable and efficient computational algorithms. To mathematically describe systems with faults, both additive fault models as well as physical fault models can be used. To address the robustness aspects, LPV models (with explicit dependence of varying parameters) or multiple LTI models (with implicit dependence of parameters) can be recast such that (fictitious) noise inputs account for the effects of parameter variations. Chapter 3 discusses the main aspects related to the fault diagnosis topic, as residual generation and evaluation, definition and characterization of the basic fault detectability and isolability concepts, formulation of six "canonical" problems for exact or approximate synthesis of fault detection filters, and the selection of appropriate thresholds for decision making. For all six formulated fault detection problems conditions for the existence of a solution are given. In Chap. 4, the model detection topic is discussed, by covering the generation of a structured set of residuals, definition and characterization of the model detectability concept, formulation of exact and approximate model detection problems, and selection of thresholds for decision making.

Part II—Synthesis of Residual Generators. The second part of the book is concerned with the synthesis procedures of residual generators. Chapter 5 is the central part of the book and presents conceptual synthesis procedures for the solution of the FDI problems formulated in Chap. 3. A common synthesis paradigm of all procedures is the use of the nullspace method as the first synthesis step, to reduce all synthesis problems to a simple standard form, which allows for easily checking the solvability conditions and to address least-order synthesis aspects. The selection of thresholds suitable for decision making is discussed for each of the approximate synthesis methods. Chapter 6 presents the synthesis procedures for solving the model detection problems formulated in Chap. 4. Once again, the nullspace method is used at the first step of both the exact and approximate synthesis procedures to simplify the formulation of the model detection problems and allow checking the existence conditions of a solution. The main computational aspects of the presented synthesis procedures are discussed in Chap. 7, focusing more on an informative presentation rather than on algorithmic details. The discussion of numerical aspects of the synthesis algorithms, such as the numerical stability or reliability, algorithmic performance, choice of underlying synthesis models, model conditioning, is rare in the fault detection related literature. A common basic procedural framework of all presented procedures is the use of updating techniques of the different representation forms of fault detection filters (i.e., implementation, internal). As a consequence, each synthesis procedure produces a factored representation of the fault detection filter, where partial syntheses achieved at intermediate synthesis steps may represent valid solutions satisfying partial synthesis goals. The main computational aspects, as the application of the nullspace method, least-order synthesis, coprime factorization techniques, and the solution of exact or approximate model-matching problems are presented from the fault detection perspective. Chapter 8 presents several case studies related to flight control applications, as the isolation and identification of flight actuator faults and reliable isolation of air data sensor failures.

Part III – Background Material. This part includes a substantial amount of background material on advanced system theoretical concepts and specialized computational algorithms. Chapter 9 deals with the presentation of basic concepts and results on rational and polynomial matrices, followed by the discussion, in parallel, of similar aspects in terms of equivalent descriptor system representations. Chapter 10 presents in detail the main algorithms for descriptor systems, which underlie the computational procedures of this book. For readers interested in the algorithmic details, this will allow the understanding in depth of algorithmic subtleties of the basic computations. Software implementations are available for all of the presented algorithms, implemented either in Fortran 77 and available in the SLICOT subroutine library, or as MATLAB functions accompanying this book. The presentation of the underlying algorithms is intentionally done only in the final chapter of the book, to relieve the casual readers of the need to understand highly sophisticated numerical algorithms.

1.3 Notes and References

Several monographs and textbooks partly overlap with our book, especially in the formulation of the main synthesis problems [14, 20, 26, 48, 65]. Statistical approaches for decision making are considered in [7, 14, 48]. Data-driven methods for fault diagnosis are presented in [27]. The use of sliding-mode control techniques to address both fault diagnosis and fault-tolerant control problems is the subject of the monograph [1].