Chapter 2
Basic Ideas, Major Issues and Tools in the Observer-Based FDI Framework

In this chapter, we shall review the historical development of the observer-based FDI technique, the major issues and tools in its framework and roughly highlight the topics addressed in this book.

2.1 On the Observer-Based Residual Generator Framework

The core of the model-based fault diagnosis scheme shown in Fig. 1.5 is a process model running parallel to the process. Today, it would be quite natural for anyone equipped with knowledge of the advanced control theory to replace the process model by an observer, in order to, for instance, increase the robustness against the model uncertainties, disturbances, and deliver an optimal estimate of the process output. But, thirty years ago, the first observer-based FDI system proposed by Beard and Jones marked a historical milestone in the development of the model-based fault diagnosis. The importance of their contribution lies not only in the application of observer theory, a hot research topic at that time in the area of the advanced control theory, to the residual generation, but also in the fact that their work creates the foundations for the observer-based FDI framework and opened the door for the FDI community to the advanced control theory. Since that time, progress of the observer-based FDI technique is closely coupled with the development of the advanced control theory. Nowadays, the observer-based FDI technique is an active field in the area of control theory and engineering.

Due to the close relation to the observer study, the major topics for the observer-based residual generator design are quite similar to those concerning the observer design, including:

- observer/residual generator design approaches
- reduced order observer/residual generator design and
- minimum order observer/residual generator design.

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The major tools for the study of these topics are the linear system theory and linear observer theory. A special research focus is on the solution of the so-called Luenberger equations. In this book, Chap. 5 will address these topics.

It is well known that system observability is an important pre-requisite for the design of a state observer. In the early development stage of the observer-based FDI technique, system observability was considered as a necessary structural condition for the observer construction. It has often been overlooked that diagnostic observers (i.e., observers for the residual generation or diagnostic purpose) are different from the well-known state observers and therefore deserve particular treatment. The wide use of the state observers for the diagnostic purpose misled some researchers to the erroneous opinion that for the application of the observer-based FDI schemes the state observability and knowledge of the state space theory would be indispensable. In fact, one of the essential differences between the state observer and diagnostic observer is that the latter is primarily an *output observer* rather than a state observer often used for control purposes.

Another misunderstanding of the observer-based FDI schemes is concerning the role of the observer. Often, the observer-based FDI system design is understood as the observer design and the FDI system performance is evaluated by the observer performance. This leads to an over-weighted research focus on the observer-based residual generation and less interest in studying the residual evaluation problems. In fact, the most important role of the observer in an FDI system is to make the generated residual signals independent of the process input signals and process initial conditions. The additional degree of design freedom can then be used, for instance, for the purpose of increasing system robustness.

2.2 Unknown Input Decoupling and Fault Isolation Issues

Several years after the first observer-based FDI schemes were proposed, it was recognized that such FDI schemes can only work satisfactorily if the model integrated into the FDI system describes the process perfectly. Motivated by this and coupled with the development of the unknown input decoupling control methods in the 1980s, study on the observer-based generation of the residuals decoupled from unknown inputs received strong attention in the second half of the 1980s. The idea behind the unknown input decoupling strategy is simple and clear: if the generated residual signals are independent of the unknown inputs, then they can be directly used as a fault indicator. Using the unknown input observer technique, which was still in its developing phase at that time, Wünnenberg and Frank proposed the first unknown input residual generation scheme in 1987. Inspired and driven by this promising work, unknown input decoupling residual generation became one of the most addressed topics in the observer-based FDI framework in a very short time. Since then, a great number of methods have been developed. Even today, this topic is still receiving considerable research attention. An important aspect of the study on unknown input decoupling is that it stimulated the study of the robustness issues in model-based FDI.

During the study on the unknown input decoupling FDI, it was recognized that the fault isolation problem can also be formulated as a number of unknown input decoupling problems. For this purpose, faults are, in different combinations, clustered into the faults of interest and faults of no interest which are then handled as unknown inputs. If it is possible to design a bank of residual generators that solves unknown input decoupling FDI for each possible combination, a fault isolation is then achieved.

Due to its duality to the unknown input decoupling FDI in an extended sense, the decoupling technique developed in the advanced linear control theory in the 1980s offers one major tool for the FDI study. In this framework, there are numerous approaches, for example, the eigenvalue and eigenstructure assignment scheme, matrix pencil method, geometric method, just to mention some of them.

In this book, Chap. 6 is dedicated to the unknown input decoupling issues, while Chap. 13 to the fault isolation study.

Already at this early stage, we would like to call the reader's attention to the difference between the unknown input observer scheme and the unknown input residual generation scheme. As mentioned in the last section, the core of an observer-based residual generator is an output observer whose existence conditions are different (less strict) from those for a (state) unknown input observer.

We would also like to give a critical comment on the original idea of the unknown input decoupling scheme. FDI problems deal, in their core, with a trade-off between the robustness against unknown inputs and the fault detectability. The unknown input decoupling scheme only focuses on the unknown inputs without explicitly considering the faults. As a result, the unknown input decoupling is generally achieved at the cost of the fault detectability. In Chaps. 7 and 12, we shall discuss this problem and propose *an alternative way of applying the unknown input decoupling solutions* to achieve an optimal trade-off between the robustness and detectability.

2.3 Robustness Issues in the Observer-Based FDI Framework

From today's viewpoint, application of the robust control theory to the observer-based FDI should be a logical step following the study on the unknown input decoupling FDI. Historical development shows however a somewhat different picture. The first work on the robustness issues was done in the parity space framework. In their pioneering work, Chow and Willsky as well as Lou et al. proposed a performance index for the optimal design of parity vectors if a perfect unknown input decoupling is not achievable due to the strict existence conditions. A couple of years later, in 1989 and 1991, Ding and Frank proposed the application of the $\mathcal{H}_2$ and $\mathcal{H}_\infty$ optimization technique, a central research topic in the area of control theory between the 80s and early 90s, to the observer-based FDI system design. Preceding to this work, a parametrization of (all) linear time invariant residual generators was achieved by Ding and Frank 1990, which builds, analogous to the well-known

Youla-parametrization of all stabilization controllers, the basis of further study in the $\mathcal{H}_\infty$ framework. Having recognized that the $\mathcal{H}_\infty$ norm is not a suitable expression for the fault sensitivity, Ding and Frank in 1993 and Hou and Patton in 1996 proposed to use the minimum singular value of a transfer matrix to describe the fault sensitivity and gave the first solutions in the $\mathcal{H}_\infty$ framework. Study on this topic builds one of the mainstreams in the robust FDI framework.

Also in the $\mathcal{H}_\infty$ framework, transforming the robust FDI problems into the so-called Model-Matching-Problem (MMP), a standard problem formulation in the $\mathcal{H}_\infty$ framework, provides an alternative FDI system design scheme. This work has been particularly driven by the so-called integrated design of feedback controller and (observer-based) FDI system, and the achieved results have also been applied for the purpose of fault identification, as described in Chap. 14.

Stimulated by the recent research efforts on robust control of uncertain systems, study on the FDI in uncertain systems is receiving increasing attention in this decade. Remarkable progress in this study can be observed, since the so-called LMI (linear matrix inequality) technique is becoming more and more popular in the FDI community.

For the study on the robustness issues in the observer-based FDI framework, $\mathcal{H}_\infty$ technique, the so-called system factorization technique, MMP solutions, and the LMI techniques are the most important tools.

In this book, Chaps. 7 and 8 are devoted to those topics.

Although the above-mentioned studies lead generally to an optimal design of a residual generator under a cost function that expresses a trade-off between the robustness against unknown inputs and the fault detectability, the optimization is achieved regarding to some norm of the residual generator. In this design procedure, well known in the optimal design of feedback controllers, neither the residual evaluation nor the threshold computations are taken into account. As a result, the FDI performance of the overall system, i.e. the residual generator, evaluator and threshold, might be poor. This problem, which makes the FDI system design different from the controller design, will be addressed in Chap. 12.

2.4 On the Parity Space FDI Framework

Although they are based on the state space representation of dynamic systems, the parity space FDI schemes are significantly different from the observer-based FDI methods in

- the mathematical description of the FDI system dynamics
- and associated with it, also in the solution tools.

In the parity space FDI framework, residual generation, the dynamics of the residual signals regarding to the faults and unknown inputs are presented in the form of algebraic equations. Hence, most of the problem solutions are achieved in the framework of linear algebra. This brings with the advantages that (a) the FDI system designer is not required to have rich knowledge of the advanced control theory for the application of the parity space FDI methods (b) the most computations can be completed without complex and involved mathematical algorithms. Moreover, it also provides the researchers with a valuable platform, at which new FDI ideas can be easily realized and tested. In fact, a great number of FDI methods and ideas have been first presented in the parity space framework and later extended to the observer-based framework. The performance index based robust design of residual generators is a representative example.

Motivated by these facts, we devote throughout this book much attention to the parity space FDI framework. The associated methods will be presented either parallel to or combined with the observer-based FDI methods. Comprehensive comparison studies build also a focus.

2.5 Residual Evaluation and Threshold Computation

Despite of the fact that an FDI system consists of a residual generator, a residual evaluator together with a threshold and a decision maker, in the observer-based FDI framework, studies on the residual evaluation and threshold computation have only been occasionally published. There exist two major residual evaluation strategies. The statistic testing is one of them, which is well established in the framework of statistical methods. Another one is the so-called norm-based residual evaluation. Besides of less on-line calculation, the norm-based residual evaluation allows a systematic threshold computation using well-established robust control theory.

The concept of norm-based residual evaluation was initiated by Emami-naeini et al. in a very early development stage of the model-based fault diagnosis technique. In their pioneering work, Emami-naeini et al. proposed to use the root-mean-square (RMS) norm for the residual evaluation purpose and derived, based on the residual evaluation function, an adaptive threshold, also called threshold selector. This scheme has been applied to detect faults in dynamic systems with disturbances and model uncertainties. Encouraged by this promising idea, researchers have applied this concept to deal with residual evaluation problems in the $\mathcal{H}_\infty$ framework, where the $\mathcal{L}_2$ norm is adopted as the residual evaluation function.

The original idea behind the residual evaluation is to create such a (physical) feature of the residual signal that allows a reliable detection of the fault. The $\mathcal{L}_2$ norm measures the energy level of a signal and can be used for the evaluation purpose. In practice, also other kinds of features are used for the same purpose, for instance, the absolute value in the so-called limit monitoring scheme. In our study, we shall also consider various kinds of residual evaluation functions, besides of the $\mathcal{L}_2$ norm, and establish valuable relationships between those schemes widely used in practice, like limit monitoring, trends analysis etc.

The mathematical tools for the statistic testing and norm-based evaluation are different. The former is mainly based on the application of statistical methods, while for the latter the functional analysis and robust control theory are the mostly used tools.

In this book, we shall in Chaps. 9 and 10 address both the statistic testing and norm-based residual evaluation and threshold computation methods. In addition, a combination of these two methods will be presented in Chap. 11.

2.6 FDI System Synthesis and Design

In applications, an optimal trade-off between the false alarm rate (FAR) and fault detection rate (FDR), instead of the one between the robustness and sensitivity, is of primary interest in designing an FDI system. FAR and FDR are two concepts that are originally defined in the statistic context. In their work in 2000, Ding et al. have extended these two concepts to characterize the FDI performance of an observer-based FDI system in the context of a norm-based residual evaluation.

In Chap. 12, we shall revise the FDI problems from the viewpoint of the trade-off between FAR and FDR. In this context, the FDI performance of the major residual generation methods presented in Chaps. 6–8 will be checked. We shall concentrate ourselves on two design problems: (a) given an allowable FAR, find an FDI system so that FDR is maximized (b) given an FDR, find an FDI system to achieve the minimum FAR.

FDI in feedback control systems is, due to the close relationship between the observer-based residual generation and controller design, is a special thematic field in the FDI study. In Chap. 15, we shall briefly address this topic.

2.7 Notes and References

As mentioned above, linear algebra and matrix theory, linear system theory, robust control theory, statistical methods and currently the LMI technique are the major tools for our study throughout this book. Among the great number of available books on these topics, we would like to mention the following representative ones:

- matrix theory: [68]
- linear system theory: [23, 105]
- robust control theory: [59, 198]
- LMI technique: [16]
- statistical methods: [12, 111].

Below are the references for the pioneering works mentioned in this chapter:

- the pioneering contributions by Beard and Jones that initiated the observer-based FDI study [13, 104]
- the first work of designing unknown input residual generator by Wünnenberg and Frank [184]
- the first contributions to the robustness issues in the parity space framework by Chow and Willsky, Lou et al., [29, 118], and in the observer-based FDI framework by Ding and Frank [46, 48, 52] as well as Hou and Patton [91]

- the norm-based residual evaluation initiated by Emami-naeini et al. [58]
- the FDI system synthesis and design in the norm-based residual evaluation framework by Ding et al. [38].

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