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Methods for Automated Design of Fault Detection and Isolation Systems with Automotive Applications

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Department of Electrical Engineering
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ABSTRACT

Fault detection and isolation (FDI) is essential for dependability of complex technical systems. One important application area is automotive systems, where precise and robust FDI is necessary in order to maintain low exhaust emissions, high vehicle up-time, high vehicle safety, and efficient repair. To achieve good performance, and at the same time minimize the need for expensive redundant hardware, model-based FDI is necessary. A model-based FDI-system typically comprises fault detection by means of residual generation and residual evaluation, and finally fault isolation.

The overall objective of this thesis is to develop generic and theoretically sound methods for design of model-based FDI-systems. The developed methods are aimed at supporting an automated design methodology. To this end, the methods require a minimum of human interaction. By means of an automated design methodology the overall design process becomes more efficient and systematic, which also contributes to higher quality. These aspects are of particular importance in an industrial context.

Design of a model-based FDI-system for a complex real-world system is an intricate task that poses several difficulties and challenges that must be handled by the involved design methods. For instance, modeling of these systems often result in large-scale, non-linear, differential-algebraic models. Furthermore, despite substantial modeling work, models are typically not able to capture the behaviors of systems in all operating modes. This results in model-errors of time-varying nature and magnitude. This thesis develops a set of methods able to handle these issues in a systematic manner.

Two methods for model-based residual generation are developed. The two methods handle different stages of the design of residual generators. The first method considers the actual residual generator realization by means of sequential residual generation with mixed causality. The second method considers the problem of how to select an optimal set of residual generators from all possible residual generators that can be created with the first method. Together the two methods enable systematic design of a set of residual generators that fulfills a stated fault isolation requirement. Moreover, the methods are applicable to complex, large-scale, and non-linear differential-algebraic models.

Furthermore, a data-driven method for statistical residual evaluation is developed. The method relies on a comparison of the probability distributions of residuals and exploits no-fault data from the system in order to learn the behavior of no-fault residuals. The method can be used to design residual evaluators capable of handling residuals subject to stochastic uncertainties and disturbances caused by for instance time-varying model errors.

The developed methods, as well as the potential of an automated design methodology, are evaluated through extensive application studies. To verify their generality, the methods are applied to different automotive systems, as well as a wind turbine system. The performances of the obtained FDI-systems are good in relation to the required engineering effort. Particularly, no specific adaption or no tuning of the methods, or the design methodology, were made.

POPULÄRVETENSKAPLIG SAMMANFATTNING

Syftet med denna avhandling är att utveckla metoder för automatiserad design av diagnossystem för att upptäcka och isolera fel i stora komplexa tekniska system. Att upptäcka och isolera fel är viktigt för att garantera ett systems pålitlighet och driftsäkerhet. Ett exempel är tunga lastbilar där förmågan att upptäcka och isolera fel är avgörande för att uppnå och bibehålla exempelvis låga avgasemissioner, hög nyttjandegrad, hög fordonssäkerhet och effektiva reparationer.

Ett sätt att upptäcka fel i ett system är att använda så kallade *modellbaserade residualer*. En modellbaserad residual kan skapas genom att bilda skillnaden mellan en observation från systemet och dess virtuella motsvarighet som skapas genom att simulera systemets felfria beteende med hjälp av en matematisk modell. En residual skild från noll indikerar att det kan finnas något fel i systemet. Genom att använda residualer baserade på observationer från olika delar av systemet så kan ett upptäckt fel dessutom isoleras till en specifik komponent i systemet. Detta är framförallt viktigt för effektiva reparationer.

Design av ett komplett diagnossystem för ett stort komplext system är en utmanande uppgift som kräver en ansenlig mängd utvecklingsarbete. För att erhålla en optimal lösning fodras väldefinierade krav med avseende på exempelvis robusthet och de fel som skall upptäckas och isoleras. Dessutom behövs detaljerad kunskap om systemets beteende, dels för det felfria fallet, men framförallt för alla tänkbara felfall. Denna typ av information är dock sällan tillgänglig åtminstone inte i början av en utvecklingsprocess. Med en automatiserad designmetodik så kan kontinuerliga förbättringar hos diagnossystemet göras snabbt och effektivt då nya krav och mer kunskap tillkommer. Detta innebär en systematisering och effektivisering av utvecklingsprocessen vilket i förlängningen också borgar för högre kvalité.

I avhandlingen utvecklas ett antal generella och teoretiskt välgrundade metoder för att upptäcka och isolera fel i komplexa tekniska system med hjälp av modellbaserade residualer. För att stödja en automatiserad designmetodik är metoderna utvecklade för att kräva minimal användarinteraktion. Stora komplexa system ställer höga krav på metodernas beskaffenheter. Exempelvis så beskrivs dessa system ofta utav stora dynamiska och olinjära modeller vilka måste kunna hanteras. Vidare så leder dessa systems mångfacetterade egenskaper och komplexitet till att modellerna inte alltid är kapabla att beskriva systemens beteende i alla situationer. Metoderna är utvecklade för att hantera dessa svårigheter på ett systematiskt sätt.

De utvecklade metoderna, såväl som potentialen hos en automatiserad designmetodik, utvärderas genom omfattande applikationsstudier. Metoderna appliceras med god framgång för att utveckla kompletta diagnossystem för såväl en dieselmotor i en tung lastbil som en vindkraftturbin. Slutsatsen är att metoderna kan användas för att designa ett diagnossystem med bra prestanda till en mycket liten arbetsinsats.

ACKNOWLEDGMENTS

With this thesis I have accomplished one of my goals in life, namely to write a book. It has been five years filled with hard but foremost inspiring and rewarding work. Neither the writing nor the work would have been possible without a number of individual persons.

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Introduction

1.1 Background and Motivation

The ability to detect and isolate faults in complex technical systems is important in order to fulfill dependability requirements. One important example is automotive systems, where fault detection and isolation (FDI) is necessary in order to obtain and maintain for instance high vehicle uptime, low exhaust emissions, high vehicle safety, efficient repair, and good fuel economy. Uptime, repair, and fuel economy, are important factors in order to minimize the overall life-cycle cost of an automotive vehicle, which is of great importance for vehicle operators. Exhaust emissions are important in order to fulfill strict legislative requirements but are also, together with vehicle safety, important for conscious vehicle operators.

Complex technical systems aimed at commercial use are often designed for low cost and high functionality, and not primarily to facilitate FDI. In particular, this means that there are few sensors and foremost a limited amount of hardware redundancy in the form of multiple sensors measuring the same quantity. To achieve good performance, and at the same time minimize the need for expensive redundant hardware, model-based FDI is often adopted. A model-based FDI-system typically comprises fault detection by means of the two essential steps; residual generation and residual evaluation. In the first step, a model of the system is used together with measurements to generate residuals, i.e., signals that indicate whether there is a fault in the system or not. In the second step, the residuals are evaluated with the aim to reliably detect changes in the residual behavior and make a decision whether the change is caused by faults in the system.

The inherent properties of complex real-world systems in general, and automotive systems in particular, pose several difficulties and challenges when it comes to design of model-based FDI-system. First of all, these systems are typically described by models in the form of large-scale, non-linear, and coupled differential-algebraic equations. Consequently, this kind of models must be handled in the design of a model-based FDI-system, in particular by the method used for design of residual generators. Furthermore,

1

complex systems often contain many physical interconnections which implies that the effect of a fault may propagate in the system and that the effect will be visible in many of the sensor measurements. This, in combination with the small number of sensors, makes fault isolation in these systems a non-trivial problem. For instance, the problem of fault decoupling in residual generators must be handled which in addition is further complicated by the properties of the involved models.

Furthermore, the complexity of the systems in combination with their often many operating modes, imply that models typically not are able to fully describe the behaviors of systems in all operating modes. Regardless of a substantial modeling work, this results in model-errors of time-varying nature and magnitude. In order to be able to detect small faults in a robust way, model errors and additional uncertainties must be handled. Specifically, this issue must be handled by the method used for design of residual evaluators.

1.2 OBJECTIVE

In an industrial context, and with the challenges and difficulties discussed above in mind, it is clear that design of a complete model-based FDI-system for a complex real-world system is an intricate task that demands a substantial engineering effort. To obtain an optimal design, it is required to have well-defined requirements regarding for example robustness and the faults to detect and isolate. In addition, it is required to have detailed knowledge of the behavior of the supervised system. Both in the no-fault case, but in particular also in all fault cases. This kind of information is however seldom available for real-world systems, at least not during early stages in the design process. To conform to this situation, an iterative design process is adopted in this thesis. In this way, continuous improvements of the FDI-system can be made as more knowledge is obtained and additional requirements arise along the design process.

The overall objective of the thesis is to develop generic, systematic, and theoretically sound methods for design of model-based FDI-systems for complex real-world systems. In addition, in order to facilitate the adopted iterative design process, the methods are aimed at supporting an automated design methodology and require a minimum amount of human interaction. By means of an automated design methodology, the FDI-system can be rapidly redesigned and reconfigured which makes the iterative design process more efficient and systematic, and also contributes to higher quality. All these issues are essential in an industrial context.

1.3 OUTLINE

The thesis is divided into two parts. The first part aims at providing the information necessary for placing the contributions of the second part in a scientific and industrial context. The first part consists of Chapters 2, 3, and 4. Chapter 2 discusses FDI in automotive systems with the aim to provide an application oriented background and motivation to the work carried out in the thesis. Chapter 3 considers design of FDI-

1.3. Outline

systems, both in a general and theoretical context, and in an industrial context. Finally, Chapter 4 summarizes the main contributions of the thesis.

The second part consists of five papers enclosed as Papers A - E. Papers A and B consider residual generation, and Paper C residual evaluation. Papers D and E contain application studies in the form of an automotive diesel engine system and wind turbine system, respectively. These papers demonstrate and evaluate the applicability of the methods developed in Papers A, B, and C, in particular, and the potential of an automated design methodology in general.

Fault Detection and Isolation in Automotive Systems

This chapter discusses fault detection and isolation (FDI) in the context of automotive systems. The overall aim is to provide an application oriented background and motivation to the work carried out in this thesis. The chapter is structured as follows. Section 2.1 presents some automotive systems where FDI is important, and discusses some of their characterizing properties of significance in this context. Section 2.2 elaborates on the importance of FDI as a mean to fulfill a set of requirements on automotive systems. Different activities involving FDI aimed at guarantee fulfillment of these requirements are also discussed. Finally, Section 2.3 presents a set of requirements for FDI in automotive systems. This is done from an industrial perspective, taking the properties of automotive systems in Section 2.1, as well as the properties of the different activities in Section 2.2, into account.

2.1 AUTOMOTIVE SYSTEMS

The intention with this section is to give examples of some automotive systems where FDI is important, and also of typical faults that may occur in these systems. Finally, some characteristic properties of automotive systems of particular significance in the context of FDI are highlighted.

2.1.1 EXAMPLES

A modern automotive vehicle is a complex *cyber-physical system* that contains electrical, mechanical, chemical, and thermo-dynamical, sub-systems. Of particular interest for heavy-duty vehicles is the diesel engine, which is frequently used as an application example in this thesis. In order to meet requirements in terms of fuel economy, emissions,

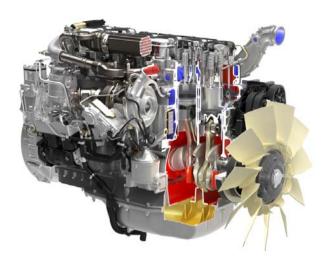


Figure 2.1: A Scania 13-liter, 6-cylinder diesel engine equipped with EGR and VGT. (Courtesy of Scania CV AB. Illustration by Semcon Informatic Graphic Solutions.)

and driveability, a modern diesel engine is equipped with for example Exhaust Gas Recirculation (EGR), Variable Geometry Turbocharger (VGT), and intake manifold throttle, see Figures 2.1, 2.2, and 2.3a. To purify exhausts, diesel engines interact with, and are dependent on, one or several advanced after-treatment systems such as a Diesel Particulate Filter (DPF), and a Selective Catalytic Reduction (SCR) system, see Figure 2.3b. In addition, to further increase driveability and meet safety requirements, they interact with other complex systems in the power train like an automatic gearbox and an auxiliary hydraulic braking system, see Figure 2.4.

2.1.2 FAULTS

All of the above mentioned systems are, due to their function and complexity, vulnerable to faults. To investigate which faults to detect and isolate, Failure Mode Effect Analysis (FMEA) (Stamatis, 1995) and Fault Tree Analysis (FTA) (Haasl et al., 1981) may be carried out. For the specific case of automotive engines, emission critical faults are of special interest. Much effort is therefore spent on testing the engines in test-beds where faults can be injected and emissions measured. Typical emission critical faults are faults affecting the fuel-injection system, the cooling system, and the gas-flow system, faults in all sensors and actuators, and faults affecting after-treatment systems like the SCR-system and the DPF. Specific examples are gas-leakages in the VGT- or EGR-system, bad UREA quality in the SCR-system, broken or missing filter substrate in the DPF, or a bias- or gain fault in a sensor. Sensors and actuators are in themselves complex cyber-physical systems, and are particularly sensitive to faults, in comparison with for example purely mechanical systems. It is therefore important that especially faults in sensors and actuators in automotive systems can be detected and isolated.

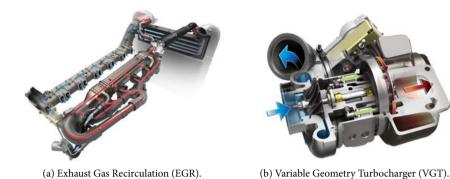


Figure 2.2: To meet requirements in terms of fuel economy, emissions, and driveability, a modern diesel engine is equipped with EGR and VGT. (Courtesy of Scania CV AB. Illustration by Semcon Informatic Graphic Solutions.)

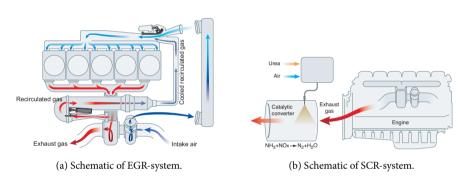


Figure 2.3: Usage of EGR and/or SCR in diesel engines reduces the generation of NOx. (Courtesy of Scania CV AB. Illustrations by Semcon Informatic Graphic Solutions.)

2.1.3 CHARACTERIZING PROPERTIES

Some characterizing properties of automotive systems, and many large real-world systems in general, of particular significance in the context of FDI, are highlighted below.

Few Sensors Automotive systems are typically designed for low cost and high functionality, and not primarily to facilitate FDI. Foremost, this means that there are few sensors in general, and in particular that there is limited, or no, hardware redundancy in the form of multiple sensors measuring the same physical quantity.

Many Operating Modes Automotive system are typically designed to operate in a number of different operating modes and normal operation usually involves several of these. For the example of a diesel engine, operating modes are typically determined by engine torque and engine speed. One operating mode is characterized by low engine speed and high engine torque, and another mode by high engine speed, but low engine torque.

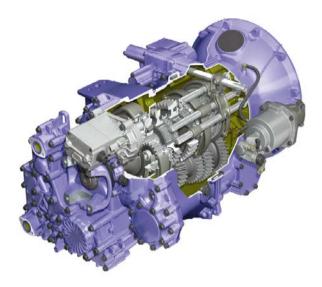


Figure 2.4: Scania GR875R 8-speed gearbox with a retarder. The retarder is a hydraulic braking system used on heavy duty trucks for long continuous braking, for example to maintain constant speed down a slope. (Courtesy of Scania CV AB. Illustration by Semcon Informatic Graphic Solutions.)

Highly Interconnected Automotive systems often contain many physical interconnections. For an example, the exhaust and intake parts of the diesel engine depicted in Figure 2.1 are coupled by means of the shaft connecting the turbine and the compressor. This implies that the effect of a fault may propagate in the system and effects will be visible in many of the measurements.

Complex Models Typically, physical modeling based on first principles of physics is utilized for modeling of automotive systems. As a consequence of the inherent complexity of automotive systems, as well as their multi-domain features, modeling typically results in large-scale, highly non-linear, differential-algebraic equations. In addition, due to the many interconnections in the systems, models are often highly coupled.

2.2 IMPORTANCE OF FAULT DETECTION AND ISOLATION

Automotive vehicles are designed in order to fulfill requirements in terms of:

- high vehicle uptime,
- low exhaust emissions,
- high vehicle safety,



Figure 2.5: High vehicle uptime, low exhaust emissions, high vehicle safety, as well as efficient repair, are important for the dependability of an automotive vehicle.

- · efficient repair,
- · good fuel economy,
- high driveability.

High *vehicle uptime* together with efficient *repair*, in the sense that the time at the workshop is minimized, maximizes the possible revenue for a vehicle operator. Good *fuel economy* and efficient repair, in the sense that no unnecessary parts are changed, minimizes the vehicle cost. Vehicle uptime, repair, and fuel economy, are thus all important factors in order to minimize the overall life-cycle cost of an automotive vehicle. This, in combination with high *safety* and high *driveability*, is of great importance for vehicle operators. Requirements on low *exhaust emissions* are mainly driven by legislations.

The properties high vehicle uptime, low exhaust emissions, high safety, as well as efficient repair, are all examples of the more general dependability (Laprie, 1992; Storey, 1996) attributes *availability*, *reliability*, *safety*, *integrity*, and *maintainability*, see Figure 2.5.

A fault in the vehicle or any of its sub-systems may lead to a failure in the form of an impairment of any of the required properties listed above, for instance in the form of a standstill vehicle, increased exhaust emissions, or a non-functional braking system. Such consequences may be prevented, or at least reduced, if the fault can be detected, isolated, and accommodated. Thus, FDI is a mean in order to achieve the properties above.

To ensure achievement of the required properties, FDI is performed by means of the three activities:

- legislative on-board diagnosis,
- off-board diagnosis,
- on-board fault accommodation.

For an illustration, see Figure 2.6. These activities may be performed independently, but typically there are dependencies. For instance, results from legislative on-board diagnosis may be exploited for off-board diagnosis at the workshop. Nevertheless, the ability to be able to detect and isolate faults, to some extent, is important for all three activities. Next, the different activities will be discussed.

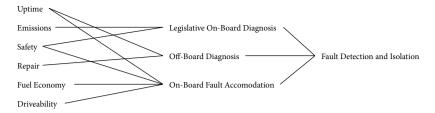


Figure 2.6: Legislative on-board diagnosis, off-board diagnosis, and on-board fault accommodation, are important activities in order to achieve properties such as high vehicle uptime, low exhaust emissions, high safety, efficient repair, good fuel economy, and high driveability. All these activities involve fault detection and isolation.

2.2.1 LEGISLATIVE ON-BOARD DIAGNOSIS

The on-board diagnosis (OBD) legislations (United Nations, 2008; European Parliament, 2009; California EPA, 2010; United States EPA, 2009) state that all manufactured automotive vehicles must be equipped with a high precision OBD-system capable of detecting faults in all components that, if broken, lead to emissions over pre-defined OBD-thresholds during a specific driving cycle. In addition, it is required that emission critical faults can be isolated. In the OBD-legislations, faults are classified according to their emission criticality and different classes requires different actions. A sufficient action for most faults is activation of a malfunction indicator light (MIL), but severe faults require engine torque limitation, or even engine shutdown. OBD is performed in electronic control units (ECUs), as the vehicle operates on the road. For heavy-duty trucks, emissions of especially nitrogen oxides (NOx) and particulate matter (PM) are crucial. Upcoming legislations in the European Union, Euro VI, require substantially lowered emissions, see Table 2.1.

The upcoming functional safety standard ISO 26262 may result in legislative requirements for faults that may lead to an impairment of the vehicle safety. This will require additional FDI and substantially increase the amount of legislative on-board diagnosis.

2.2.2 OFF-BOARD DIAGNOSIS

Off-board diagnosis refers to activities performed off-board the vehicle, typically in the workshop by a mechanic and with additional external computer support. In this setting, FDI can be combined with decision-theoretic troubleshooting, see, e.g., Heckerman et al. (1995); Langseth and Jensen (2002); Warnquist (2011), in order to not only locate but also replace faulty components. The overall aim of off-board fault diagnosis is to guarantee efficient repair of the vehicle, which in turn contributes to high vehicle uptime.

Due to hardware limitations on-board the vehicle and the ability to actively excite systems when the vehicle is at the workshop, off-board detection and isolation of faults potentially give better and more precise results for repair purposes. In addition, it is possible to exploit more knowledge and information from, and regarding, the vehicle in an off-board setting, and to use more powerful fault isolation methods, e.g., Bayesian fault

Tier	Date	Test	CO	HC	NOx	PM	Smoke
Euro I	1992, < 85 kW	ECE R-49	4.5	1.1	8.0	0.612	
	1992, > 85 kW		4.5	1.1	8.0	0.36	
Euro II	1996-10		4.0	1.1	7.0	0.25	
	1998-10		4.0	1.1	7.0	0.15	
Euro III	1999-10, EEVs only	ESC & ELR	1.5	0.25	2.0	0.02	0.15
	2000-10	ESC & ELR	2.1	0.66	5.0	0.1	0.8
						0.131	
Euro IV	2005-10		1.5	0.46	3.5	0.02	0.5
Euro V	2008-10		1.5	0.46	2.0	0.02	0.5
Euro VI	2013-01		1.5	0.13	0.4	0.01	
		2					

Table 2.1: EU Emission Standards for HD Diesel Engines, g/kWh (smoke in m⁻¹)

isolation (Jensen and Nielsen, 2007; Schwall and Gerdes, 2002; Pernestål and Warnquist, 2012). Examples of additional knowledge and information may be measurements and on-board diagnosis results from all ECUs in the vehicle, and history from previous workshop visits, etc. These issues greatly contribute to better and more precise FDI results. Nevertheless, despite the quite different prerequisites, FDI is of great importance also in the context of off-board diagnosis.

2.2.3 ON-BOARD FAULT ACCOMMODATION

On-board fault accommodation, or fault management, is performed in ECUs on-board the vehicle during operation on the road. The aim of on-board fault accommodation is to prevent detected and isolated faults from developing into critical failures by taking appropriate actions, and thereby guarantee high vehicle uptime, high safety, high driveability, and also good fuel economy. With upcoming requirements such as the functional safety standard ISO 26262, it is likely that the amount of safety related fault accommodation will increase.

Typically, different faults require different actions. A common action is reconfiguration of the control system by means of fault tolerant control (FTC), see, e.g., Blanke et al. (2006); Yang et al. (2010). For instance, a fault in a sensor used in closed-loop control is accommodated by switching to open-loop control or by instead using a virtual alternative, e.g., a modeled value, to the faulty sensor and maintain closed-loop control. Some critical faults may however require more intricate actions such as system shutdown. In order to conduct the best possible action at any time, it is important to know which fault that has occurred and thus fault isolation is important also in the context of on-board fault accommodation.

¹ for engines of less than 0.75 dm³ swept volume per cylinder and a rated power speed of more than 3000 min⁻¹

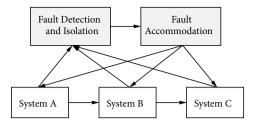


Figure 2.7: Centralized fault accommodation.

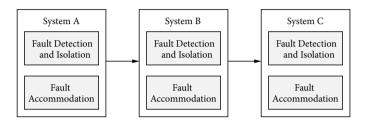


Figure 2.8: Decentralized fault accommodation.

CENTRALIZED AND DECENTRALIZED FAULT ACCOMMODATION

Traditionally in the literature, *centralized fault accommodation* is adopted, where a centralized FDI unit is used together with a centralized fault accommodation manager, see, e.g., Blanke et al. (2006), and Figure 2.7. However, this creates extra dependencies which increase the complexity and thus this approach is non-modular and scales badly with the size of the system.

Therefore, for large scale automotive systems with functionality distributed over several ECUs, *decentralized fault accommodation* may be more appropriate in order to handle the inherent complexity and making the fault accommodation problem more tractable, see Nyberg and Svärd (2010a,b). Using this approach, the FDI, as well as the fault accommodation, is performed locally in a distributed manner, see Figure 2.8. Independent of which fault accommodation approach that is adopted, FDI is nevertheless needed.

2.3 REQUIREMENTS ON FDI IN AUTOMOTIVE SYSTEMS

The properties of automotive systems discussed in Section 2.1.3, in combination with the attributes of the different activities discussed in Section 2.2, impose certain requirements on how FDI is performed from and industrial perspective. The most important of these, in the context of this thesis, are listed below.

Existing Hardware Due to cost reasons and space limitations, it is not a desired option to mount additional hardware in the form of for instance multiple sensors, in order

to detect and isolate faults. Thus, FDI in automotive systems should be performed by using existing hardware only.

- Small Faults As said, the OBD-legislations require detection of all faults that may lead to increased exhaust emissions. Typically, this require detection of small faults in particularly sensor and actuators. For instance, many emission related automotive systems, e.g., the SCR-system, are dependent on correct sensor values for control and, as said in Section 2.1.2, sensors are particularly prone to faults. Even such a small fault as a deviation of a sensor value by 10 % may lead to incorrect control of these systems, which in turn may lead to increased emissions.
- On-Board Implementation Apart from the particular case of off-board diagnosis, FDI is to be performed in an on-board environment subject to constraints on computational power and memory, and in some cases also on strict computational deadlines, i.e., real-time. Thus, it is desirable that the FDI can be performed in this environment.
- **Robustness** The many operating modes of automotive systems, as discussed in Section 2.1.3, in combination with the urge to be able to handle different vehicle configurations and vehicle individuals, pose strict requirements on the robustness of the FDI.
- **Systematic Design** In order to obtain an *FDI-system* of high quality, and at the same time enable reconfiguration, redesign, and an efficient overall design process, it is desirable that the methodology used to design the system is systematic.

These requirements will be further considered in the next chapter, in which design of FDI-systems is considered.

Design of Fault Detection and Isolation Systems

While Chapter 2 aimed at providing an application oriented motivation and background to the work in this thesis, the overall purpose of this chapter is to place the contributions in a scientific and industrial context. To this end, this chapter considers design of fault detection and isolation (FDI) systems, first from a general point of view, and then in the context of automotive systems and Chapter 2. The chapter is structured as follows. In Sections 3.1 and 3.2 some theoretical concepts from the field of model-based diagnosis in general, and FDI in particular, are briefly introduced. For further details, refer to for instance Blanke et al. (2006); Chen and Patton (1999); Hamscher et al. (1992). Section 3.3 discusses some difficulties and challenges that are encountered and must be handled when designing FDI-systems for automotive systems under the prerequisites discussed in Chapter 2. In Section 3.4, design of FDI-systems in an industrial context is discussed and the automated design methodology adopted in this thesis is presented.

3.1 FAULT DETECTION AND ISOLATION SYSTEMS

A typical FDI-system consists of a set of *fault detection tests* and a *fault isolation scheme*, see Figure 3.1. The input to the FDI-system is a set of *observations*, i.e., measurements, from the supervised system, and the output is a *diagnosis statement*. The diagnosis statement contains a collection of faults that can be used to explain the observations.

Given a set of observations, \mathbf{y} , the outcome of a detection test τ_i is a binary fault detection result, d_i , equal to for instance 1 if the test has alarmed, or equal to 0, otherwise. To enable fault isolation, different detection tests typically monitors different faults, and thus different parts of the system. Each fault detection test typically utilizes a subset of the observations in order to determine if any fault is present in its monitored part of the system.

Common traditional approaches for construction of fault detection tests are for example *limit checking*, i.e., to check if a sensor is within its normal operating range, or

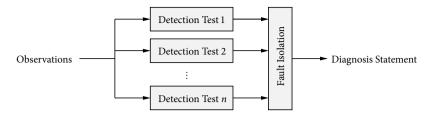


Figure 3.1: A typical FDI-system consists of a set of fault detection tests and a fault isolation scheme.

to employ *hardware redundancy*. For instance, if two sensors are used to measure the same physical quantity, it is possible to test if one of the sensors is faulty by comparing the values of the sensors. Another approach, providing potentially increased diagnosis performance and in which the need of additional, redundant, hardware is avoided, is to use detection tests based on *residuals*. Detection tests based on residuals will be further discussed in Section 3.2.

3.1.1 FAULT ISOLATION

There are several approaches for fault isolation, most originating from the field of Artificial Intelligence (AI), see, e.g., de Kleer and Williams (1987); Reiter (1987); Greiner et al. (1989). Another approach is Bayesian fault isolation, see, e.g., Jensen and Nielsen (2007). Here, in order to briefly illustrate the concept of fault isolation a method referred to as *structured residuals* (Gertler, 1991), or *structured hypothesis tests* (Nyberg, 2002) will be considered.

For an example, consider a set of detection tests $\{\tau_1, \tau_2, \tau_3\}$ constructed to detect and isolate three faults, $\{f_1, f_2, f_3\}$. The following *fault signature matrix*,

shows which tests that are *sensitive* to which faults, i.e., test τ_1 is sensitive to faults f_2 and f_3 , and so on. Now assume a situation where tests τ_1 and τ_2 , but not τ_3 , have alarmed. The outcome from the detection tests are thus $d_1 = 1$, $d_2 = 1$, and $d_3 = 0$, which combined with the fault signature matrix (3.1) results in the *sub-diagnosis statements* $D_1 = \{f_2, f_3\}$, $D_2 = \{f_1, f_3\}$, and $D_3 = \{f_1, f_2, f_3\}$. The latter is due to a common convention, saying that nothing can be deduced regarding the status of the system if a test has not alarmed. The diagnosis statement $\mathcal D$ then becomes

$$\mathcal{D} = D_1 \cap D_2 \cap D_3 = \{f_2, f_3\} \cap \{f_1, f_3\} \cap \{f_1, f_2, f_3\} = \{f_3\},$$

and it can be concluded that fault f_3 is present. In general, considering an FDI-system containing the detection tests $\{\tau_1, \tau_2, \dots, \tau_n\}$, where the outcome of the test τ_i is a

detection result d_i with a corresponding sub-diagnosis statement D_i . Under a single fault assumption, the diagnosis statement \mathcal{D} can be obtained as

$$\mathcal{D} = \bigcap_{i=1}^n D_i,$$

for multiple faults, see, e.g., de Kleer and Williams (1987).

3.2 DETECTION TESTS BASED ON RESIDUALS

A residual is a signal ideally zero in the no-fault case and non-zero otherwise. A *residual* generator, R_i , takes measurements, \mathbf{y} , from the supervised system as input, and produces a residual, r_i , as output, i.e., $r_i = R_i(\mathbf{y})$. A common way to construct a fault detection test based on a residual is to evaluate its behavior in order to conclude whether or not a fault is present in its monitored part of the system. This is done by means of a *residual* evaluator, T_i , taking a residual r_i as input and producing a detection test result d_i as output, i.e., $d_i = T_i(r_i)$. Typically, residual evaluation is performed by forming a test quantity from the residual and then threshold the test quantity. In this case, a detection test τ_i based on the residual $r_i = R_i(\mathbf{y})$, by means of a residual evaluator $d_i = T_i(r_i)$, has the form

$$d_{i} = \tau_{i}\left(\mathbf{y}\right) = T_{i}\left(R_{i}\left(\mathbf{y}\right)\right) = \begin{cases} 1 & \text{if } \lambda_{i}\left(r_{i}\right) > J_{i} \\ 0 & \text{if } \lambda_{i}\left(r_{i}\right) \leq J_{i}, \end{cases}$$
(3.2)

where λ_i is a test quantity, and J_i is a detection threshold. Methods for residual generation and residual evaluation will be discussed in Sections 3.2.2 and 3.2.3, respectively.

In Figure 3.2, a residual r and test quantity λ created for fault detection in an automotive diesel engine are shown. A fault occurs at t=700 s. First of all, it is noted that the behavior of the residual r is non-ideal, in the sense that the residual is non-zero both in the no-fault and fault cases. Moreover, it can be seen that the response of the residual to the fault is subtle. Nevertheless, as indicated by the behavior of the test statistic λ , the fault can be detected by an appropriate residual evaluation.

3.2.1 STRUCTURE OF FDI-SYSTEMS BASED ON RESIDUALS

An FDI-system with fault detection tests based on residuals typically have the structure shown in Figure 3.3. Observations \mathbf{y} in the form of measurements from the supervised system are used as input to a residual generation block, which contains a set of residual generators, R_1, R_2, \ldots, R_n . The output from the residual generation block is a set of residuals r_1, r_2, \ldots, r_n , with $r_i = R_i(\mathbf{y})$. The residuals r_1, r_2, \ldots, r_n are used as input to the residual evaluation block, which contains a set of residual evaluators, T_1, T_2, \ldots, T_n . The output from the residual evaluation block is a set of fault detection results, d_1, d_2, \ldots, d_n , with $d_i = T_i(r_i)$. These are used as input to the fault isolation block, where the detected fault(s) are isolated.

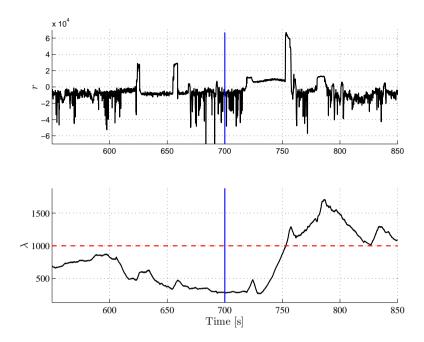


Figure 3.2: A residual r (top) and test quantity λ (bottom) created for fault detection in an automotive diesel engine. The red dashed line is the detection threshold J. A fault occurs at t = 700 s. Note the non-ideal behavior of the residual and its subtle response to the fault. By an appropriate residual evaluation by means of the test quantity λ , the fault can nevertheless be detected.

3.2.2 RESIDUAL GENERATION

Typically, residual generators are constructed by using a mathematical model of the system. For instance, a residual can be obtained as the comparison between a value estimated by a model and the corresponding measured quantity. The residual generator consists in this case of the model used for the estimation and the equation describing the comparison, referred to as the *residual equation*.

One approach to residual generation that is of particular interest in this thesis is *sequential residual generation*, see, e.g., Staroswiecki and Declerck (1989); Cassar and Staroswiecki (1997); Staroswiecki (2002); Pulido and Alonso-González (2004); Ploix et al. (2005); Travé-Massuyès et al. (2006); Blanke et al. (2006). This approach has shown to be successful for real applications (Dustegor et al., 2006, 2004; Izadi-Zamanabadi, 2002; Cocquempot et al., 1998), and in addition has the potential to be automated to a high extent.

Additional approaches include for instance *observer-based residual generation*, see, e.g., Massoumnia et al. (1989); Hammouri et al. (2001); De Persis and Isidori (2001); Li and Kadirkamanathan (2001); Martínez-Guerra et al. (2005); Kaboré et al. (2000); Hou (2000); Patton and Hou (1998); Gao and Ding (2007); Vemuri et al. (2001); Shields (1997),

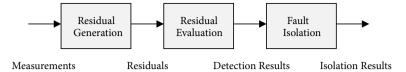


Figure 3.3: An FDI-system with fault detection tests based on residuals by means of residual generation and residual evaluation.

parity-space methods, e.g., Chow and Willsky (1984); Nyberg and Frisk (2006); Varga (2003), and *frequency domain methods*, e.g., Frank and Ding (1994).

FAULT DECOUPLING

To achieve a specific fault signature matrix, for example one similar to (3.1), decoupling of faults in residuals is needed. The faults that are decoupled are referred to as non-monitored faults, whereas the faults not decoupled are called monitored faults. In the example of Section 3.1.1, fault f_1 is decoupled in τ_1 , which means that for τ_1 , fault f_1 is a non-monitored fault and f_2 and f_3 are monitored faults. Decoupling of faults in a set of tests based on residuals, means that the residuals must be sensitive to different subsets of faults.

In the context of fault isolation, *fault decoupling* is a fundamental problem in residual generation. In most of the observer-based residual generation methods mentioned above, decoupling of faults is obtained by transforming the original model into a submodel where only the faults of interest are present. In sequential residual generation methods, the original model is often divided into sub-models with specific properties and residual generators are then designed for each sub-model. Since a residual generator only is sensitive to those faults affecting its corresponding sub-model, all other faults are decoupled.

3.2.3 RESIDUAL EVALUATION

As said, the aim of residual evaluation is to detect changes in the residual behavior caused by faults in the system. Typical components of a residual evaluator are a test quantity λ_i and detection threshold J_i , see (3.2). There are, in essence, two main approaches (Ding et al., 2007) for design of the test quantity and threshold; *statistical residual evaluation* (Willsky and Jones, 1976; Gertler, 1998; Basseville and Nikiforov, 1993; Peng et al., 1997; Al-Salami et al., 2006; Blas and Blanke, 2011; Wei et al., 2011), and *norm-based residual evaluation* (Emami-Naeini et al., 1988; Frank, 1995; Frank and Ding, 1997; Sneider and Frank, 1996; Chen and Patton, 1999; Zhang et al., 2002; Zhong et al., 2007; Ingimundarson et al., 2008; Al-Salami et al., 2010; Li et al., 2011; Abid et al., 2011). In the statistical approach, the framework of statistical hypothesis testing is exploited for design of the test quantity, or test statistic, which typically is based on a likelihood ratio (Gustafsson, 2000). In norm-based approaches, the test quantity is instead based on some norm of the residual, e.g., the mean-power.

Uncertainties

Typically, and as was illustrated in Figure 3.2, residuals are not perfectly zero in the no-fault case due to uncertainties in the form of for example model errors and measurement noise. This may decrease the ability to detect faults and also lead to false detections. The approach used to design the test quantity and threshold in (3.2) are thus important means in order to handle uncertainties and thus guarantee good fault detection. For both statistical and norm-based residual evaluation, *adaptive thresholds* (Clark, 1989; Frank, 1994; Sneider and Frank, 1996) is a traditional approach to handle uncertainties.

The non-ideal behavior of the residual r in Figure 3.2 is a direct consequence of uncertainties in the form of model errors. As illustrated by the fact that the fault nevertheless can be detected by means of the test statistic λ , these uncertainties are handled by proper residual evaluation.

3.3 Design Challenges for Automotive Systems

In Section 2.1.3, it was concluded that automotive systems typically are equipped with few sensors, have many operating modes, contain many physical interconnections, and are described by complex models. Further, it was in Section 2.3 required that FDI in automotive systems should be done in order to, as far as possible, only use existing hardware, be able to detect small faults, be implementable in an on-board environment, and also be robust against uncertainties. In addition, it was concluded that all these desired properties should be achieved by means of a systematic and efficient design methodology.

The prerequisites in terms of the properties of automotive systems, in combination with the requirements on the FDI for these systems, pose several challenges and difficulties that must be handled by the methods used for design of the FDI-system.

FAULT DECOUPLING

As said earlier, fault decoupling is essential in order to obtain fault isolation. The fact that automotive systems typically not are equipped with multiple sensors from start, in combination with the requirement to only use existing hardware for FDI, implies that it is necessary to employ analytical redundancy and model-based FDI in order to obtain good performance. This typically leads to an FDI-system with detection tests based on model-based residuals, as was considered in Section 3.2.

In addition, the many physical interconnections in an automotive system implies that the effect of a fault may propagate in the system and that the effects will be visible in many of the measurements. This fact, in combination with the small number of sensors, makes decoupling of faults a non-trivial problem. Thus, it is of great importance that the methods used to design an automotive FDI-system, in particular the residual generation method, are able to handle this issue. Regarding the requirement concerning systematic design, it is important that the residual generation method facilitates fault decoupling in a systematic manner.

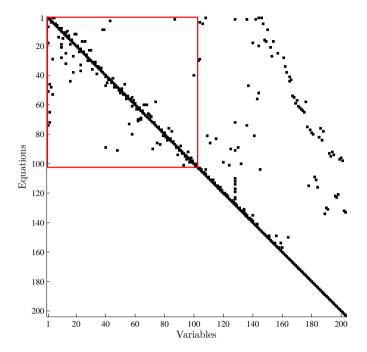


Figure 3.4: The structure of a part of a model of an automotive diesel engine where the rows correspond to model equations and columns to variables in the model. A black square in position (i, j) indicates that equation i contains variable j. The red square illustrates a coupled part of the model corresponding to a differential-algebraic loop. It may be noted the loop involves almost 50% of the equations. A fault affecting any of the equations in the coupled part of the model will influence all other equations in that part.

Model Complexity

As said, automotive systems in general, and automotive diesel engines in particular, yield models in the form of large-scale, non-linear, and coupled differential-algebraic equations. The methods used in the design of the FDI-system, in particular the residual generation method, must thus be able to handle such models in a systematic manner. Moreover, regarding the requirement concerning on-board implementability of automotive FDI-systems, it is important that the output of the residual generation method, i.e., the set of residual generators, is suitable for implementation in an on-board environment despite the complexity of the model used as input.

As said, models of automotive systems are often coupled due to the many interconnections in these systems. In particular, this results in algebraic and differential loops or cycles (Blanke et al., 2006; Katsillis and Chantler, 1997) comprised of sets of equations that contains the same set of unknown variables. This is illustrated in Figure 3.4 which shows the *structure*, i.e., which equations that contain which unknown variables, of a part of a model of an automotive diesel engine. It may be noted that the loop shown in

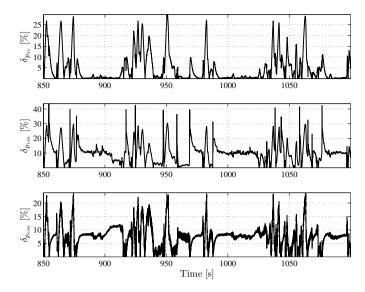


Figure 3.5: Relative model errors for the intercooler manifold pressure $p_{\rm im}$, intake manifold pressure $p_{\rm im}$, and exhaust manifold pressure $p_{\rm em}$, for a model of an automotive diesel engine during a part of the World Harmonized Transient Cycle (WHTC). Note that the magnitude of the model errors vary with time.

Figure 3.4 involves almost 50 % of the equations in the model.

Uncertainties

Due to the inherent complexity of automotive systems, in combination with their many operating modes, models are typically not capable of capturing the behaviors of systems in all different operating modes. This results in uncertainties in the form of model errors, in particular stationary errors (Höckerdal et al., 2011a,b), regardless of substantial modeling work. In addition, due to the typically unfriendly environment in terms of for example high temperatures in or around automotive systems, there are also uncertainties in the form of measurement errors and noise in sensors.

Typically, the magnitudes and nature of these uncertainties are different for different operating modes. For example, the model may be more accurate in one operating mode than another, and a sensor may be more or less sensitive to noise in different operating modes. Since the operating mode of the system varies with time, so does the magnitudes and nature of the uncertainties. This is illustrated in Figure 3.5, which shows relative model errors for three state-variables in a model of an automotive diesel engine during a part of the World Harmonized Transient Cycle (WHTC). Clearly, the magnitude of the model errors vary with time. To meet the posed requirements regarding small faults and robustness, this issue must be handled by the FDI-system. In particular, uncertainties may lead to residuals with the non-ideal behavior illustrated in Figure 3.2 and in order to

be able to detect small faults, it is important that uncertainties are handled in the residual evaluation.

3.4 AUTOMATED DESIGN OF FDI-SYSTEMS

Taking the challenges discussed in Section 3.3 into account, it is clear that design of a complete FDI-system for an automotive system, and large-scale real world systems in general, is an intricate and complex task that demands a substantial engineering effort. To obtain an optimal design, it is required to have well-defined requirements regarding for example robustness and the faults to detect and isolate, as well as detailed knowledge of the behavior of the supervised system both in the no-fault case, but in particular also in all fault cases. However, this kind of information is seldom available for real systems, at least not during early stages in the design process.

Conforming to this situation, an iterative design methodology is adopted in this thesis. In this way, continuous improvements of the FDI-system can be made as more knowledge is obtained and additional requirements arise along the design process. To support rapid redesign and reconfiguration, and in this sense make the overall design process more efficient, it is desirable to automate as many steps as possible of the design methodology. In addition, an automated methodology makes the design process more systematic which also contributes to higher quality.

3.4.1 Design Methodology

The considered design methodology is conceptually illustrated in Figure 3.6. The methodology supports design of the residual generation and residual evaluation blocks in an FDI-system with a structure in accordance with Figure 3.3.

The methodology is comprised of three main design stages. Firstly, residual generators are designed given a model of the supervised system and requirements regarding which faults to detect and isolate, robustness, computational power and memory. Design of residual generators is in this work, as in Nyberg (1999); Krysander (2006); Nyberg and Krysander (2008), considered to be a two-step approach, see Figure 3.7. In the first step, given the model, a large number of *candidate residual generators* is found, and in the second step a set of residual generators fulfilling the given requirements is selected and *realized*, i.e., put in a form suitable for implementation.

In the second stage, given the set of residual generators from the first stage and data in the form of measurements from the supervised system, residual evaluators are designed. The third and final stage is to evaluate the complete FDI-system with respect to the given requirements. In particular, it is necessary to investigate the sensitivity of the detection tests, comprised of the residual generators and residual evaluators, to the required set of faults in the presence of uncertainties and disturbances. For this, data in the form of measurements from the supervised system in a set of representative fault-cases, is needed. The results of the evaluation are then analyzed and the process is, if necessary, repeated with revised requirements.

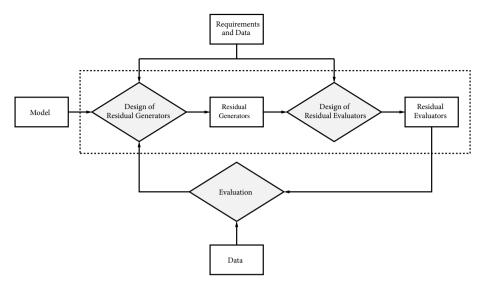


Figure 3.6: The considered methodology for design of FDI-systems.

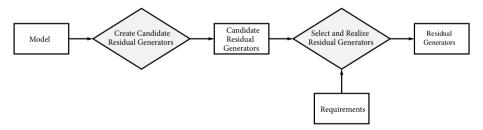


Figure 3.7: The considered two-step approach for design of residual generators.

It is noted that the available amount of fault data typically is substantially lower than the available amount of no-fault data for a number of reasons. First of all, this is due to the fact that faults are rare. To create fault data, one alternative is to inject faults in the real system. This is however considered to be expensive, both in terms of time and money, since it typically require hardware modifications and active usage of the system. Another alternative is to create fault data by simulation. To give realistic results, this on the other hand requires models capable of describing the faulty system, which in turn require detailed knowledge regarding the behavior of the faulty system and possibly also its environment. This kind of information is seldom available for real applications. Consequently, it may not be possible to exploit fault data in all stages of the design methodology, even though this is highly desirable.

Summary of Main Contributions

The overall contribution of this thesis is a set of generic and theoretically sound methods for design of FDI-systems, aimed at supporting an automated design methodology. Specifically, this thesis contributes to the part of the design methodology enclosed in the dashed area of Figure 3.6. The developed methods, as well as the overall design methodology, are evaluated through extensive application studies.

In particular, theoretical and methodological contributions are made in the areas of model-based residual generation and statistical residual evaluation in form of three papers enclosed as Paper A, Paper B, and Paper C. Technological contributions, by means of state-of-practice illustrations and proof-of-concept demonstrations, to the field of model-based FDI are made in the form of application studies in two papers enclosed as Paper D and Paper E. In addition, the application studies performed in these two papers together serve as evaluations of the methods developed in Papers A, B, and C.

In the context of the design challenges discussed in Section 3.3, model complexity and fault decoupling are considered in Papers A and B, and uncertainties in Paper C.

4.1 SUMMARIES

Brief summaries of the main contributions of Papers A - E are given below.

Paper A - Residual Generation

The main contribution of Paper A is a sequential residual generation method that enables simultaneous use of integral and derivative causality, i.e., mixed causality. In addition, the method is able to handle equation sets corresponding to algebraic and differential loops in a systematic manner, and is in this sense applicable to complex, large-scale, and coupled models of automotive systems. The method relies on a formal framework for computing unknown variables according to a computation sequence. In this framework,

mixed causality is utilized and the analytical properties of the equations in the model, as well as the available tools for algebraic equation solving, are taken into account.

In the context of the two-step approach for design of residual generators, see Figure 3.7, additional contributions are made. Firstly, it is proven that the set of residual generators that can be realized, i.e., created, with the method by necessity is a subset of the set of candidate residual generators based on all Minimal Structurally Over-determined (MSO) sets of equations (Krysander et al., 2008; Gelso et al., 2008; Pulido and Alonso-González, 2004; Travé-Massuyès et al., 2006) in the given model. Secondly, it is empirically shown that the combination of the ability to handle mixed causality and loops substantially increase the amount of realizable candidate residual generators. This is done by means of application of the method to models of two different automotive systems, a diesel engine and a hydraulic braking system.

Paper A relies partly on work presented in Svärd and Nyberg (2008a); Svärd and Nyberg (2008).

Paper B - Selection of Residual Generators

Paper B elaborates further on the two-step approach of Figure 3.7 and in particular the second step. Two different requirements on the sought set of residual generators are considered. Firstly, it is required that the set of residual generators fulfills an isolability requirement, stating which fault that should be isolated from each other. Secondly, motivated by implementation aspects, it is required that the set of residual generators is of minimal cardinality.

Two algorithms for solving the residual generator selection problem are presented in Paper B. Both algorithms exploit a formulation of the selection problem which enables an efficient reduction of the search-space by taking the realizability properties of candidate residual generators, with respect to the considered method for residual generation, into account. The first algorithm provides an exact solution fulfilling both requirements and is suitable for small problems. The second algorithm, which constitutes the main contribution, is suitable for large problems and provides an approximate solution by means of a greedy heuristic by relaxing the minimal cardinality requirement.

Soundness and completeness for both algorithms are shown. In this context, this means that the algorithms provide a set of realizable residual generators fulfilling the stated isolability requirement if, and only if, the requirement can be met with the considered residual generation method. Both algorithms are general in the sense that they are aimed at supporting any computerized residual generation method, not only the method developed in Paper A. The algorithms are applied and evaluated on an automotive diesel engine system.

A preliminary version of Paper B was presented in Svärd et al. (2011a).

Paper C - Residual Evaluation

The main contribution of Paper C is an adaptive and data-driven statistical residual evaluation method. The key property of the method is its ability to handle residuals that are subject to time-varying uncertainties and disturbances, caused for instance by

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model errors and noise. The test quantity used in the method is based on an explicit comparison of the probability distribution of the residual, estimated online using current data, with a no-fault residual distribution. The no-fault distribution is based on a set of a-priori known no-fault residual distributions, and is continuously adapted to the current situation.

The comparison is done in the framework of statistical hypothesis testing, by means of the Generalized Likelihood Ratio (GLR). To be suitable for on-line implementation in an on-board environment, a computational efficient version of the test quantity is derived by considering a properly chosen approximation to one of the likelihood maximization problems in the GLR. As a second contribution, an algorithm is proposed for learning the required set of no-fault residual distributions off-line from no-fault training data. This algorithm is based on a formulation of the learning problem as a K-means clustering problem. The residual evaluation method is demonstrated and extensively evaluated by application to a residual designed for fault detection in an automotive diesel engine.

A preliminary version of Paper C was presented in Svärd et al. (2011c).

Papers D and E - Application Studies

In Paper D, the methods for residual generation, residual generator selection, and residual evaluation, from Papers A, B, and C, respectively, are combined into an automated design methodology and applied for design of an FDI-system for an automotive diesel engine. In Paper E, the methods for residual generation and residual generator selection are combined with a preliminary version of the residual evaluation method, and applied for design of an FDI-system for the Wind Turbine Benchmark (Fogh Odgaard et al., 2009).

Papers D and E contain minor theoretical contributions. Technological contributions are however made in the sense that both works illustrate how a set of generic methods may be combined into a complete methodology in order to solve a realistic industrial FDI problem. In this sense, these works serve as an illustration of the state-of-practice in model-based fault detection and isolation. Moreover, the papers evaluate and verify the applicability of an automated design methodology in general, and the methods developed in Papers A, B, and C, in particular.

A preliminary version of Paper E was presented in Svärd and Nyberg (2011).

4.2 Publications

The research work leading to this thesis is presented in the following publications.

JOURNAL PAPERS

• C. Svärd and M. Nyberg. Residual generators for fault diagnosis using computation sequences with mixed causality applied to automotive systems. *IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans*, 40(6):1310–1328, 2010 (Paper A)

• C. Svärd and M. Nyberg. Automated design of an FDI-system for the wind turbine benchmark. *Journal of Control Science and Engineering*, vol. 2012, 2012. Article ID 989873, 13 pages (**Paper E**)

SUBMITTED

- C. Svärd, M. Nyberg, and E. Frisk. Realizability constrained selection of residual generators for fault diagnosis with an automotive engine application. Submitted to *IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans*, 2011b (Paper B)
- C. Svärd, M. Nyberg, E. Frisk, and M. Krysander. Data-driven and adaptive statistical residual evaluation for fault detection with an automotive application. Submitted to *Mechanical Systems and Signal Processing*, 2012b (Paper C)
- C. Svärd, M. Nyberg, E. Frisk, and M. Krysander. Automotive engine FDI by application of an automated model-based and data-driven design methodology. Submitted to *Control Engineering Practice*, 2012a (**Paper D**)

CONFERENCE PAPERS

- C. Svärd, M. Nyberg, and E. Frisk. A greedy approach for selection of residual generators. In *Proceedings of the 22nd International Workshop on Principles of Diagnosis (DX-11)*, Murnau, Germany, 2011a
- C. Svärd, M. Nyberg, E. Frisk, and M. Krysander. Residual evaluation for fault diagnosis by data-driven analysis of non-stationary probability distributions. In Proceedings of the 50th IEEE Conference on Decision and Control and European Control Conference (CDC-ECC 2011), 2011c
- C. Svärd and M. Nyberg. Automated design of an FDI-system for the wind turbine benchmark. In *Proceedings of 18th IFAC World Congress*, Milano, Italy, 2011
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