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Model-based approach for fault diagnosis using set-membership formulation

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ABSTRACT

This paper describes a robust model-based fault diagnosis approach that enables to enhance the sensitivity analysis of the residuals. A residual is a fault indicator generated from an analytical redundancy relation which is derived from the structural and causal properties of the signed bond graph model. The proposed approach is implemented in two stages. The first stage consists in computing the residuals using available input and measurements while the second level leads to moving horizon residuals enclosures according to an interval consistency technique. These enclosures are determined by solving a constraint satisfaction problem which requires to know the derivatives of measured outputs as well as their boundaries. A numerical differentiator is then proposed to estimate these derivatives while providing their intervals. Finally, an inclusion test is performed in order to detect a fault upon occurrence. The proposed approach is well suited to deal with different kinds of faults and its performances are demonstrated through experimental data of an omni-directional robot.

1. Introduction

A fault occurring in critical elements may lead to fatal breakdowns in equipments if it remains undetected. Such event can be catastrophic, resulting in costly downtime and may also require a lot of maintenance cost and manpower. This is why, there is an increased need for more efficient fault diagnosis approaches to monitor machine conditions in real-time and to detect the inception, progression and propagation of faults. These approaches have also been used to enable suitable decision making and to avoid, eliminate or reduce industrial risks while promoting safety (Bayar et al., 2015).

A wide variety of concepts, methods and tools have been proposed to address the aforementioned issues. Two communities have developed model-based diagnosis approaches namely the FDI (Fault Detection and Isolation) community and the Artificial Intelligence Diagnosis (DX) community (Voigt et al., 2014). Recently, the Prognostics and Health Management (PHM) community has also investigated model-based diagnosis approaches in order to generate information that enables to predict the remaining useful life of critical components within the process to be monitored (Medjaher and Zerhouni, 2013; Medjaher et al., 2012).

Most of the FDI approaches rely mainly on a set of fault indicators to carry out the fault detection and isolation stages. These indicators are called residuals and they can be generated by using parity space (Odendaal and Jones, 2014), observer based techniques (Narasimhan et al., 2008), parameters identification (Mulumba et al., 2014), graph theoretic approaches (Ould-Bouamama et al., 2014) and so on. A refined classification of these approaches can be found in Venkatasubramanian et al. (2003). Among the graphical approaches, the Bond Graph (BG) has proved its adequacy to represent energy exchanges in mixed systems and has been used to generate fault indicators in a systematic and generic way. The procedure is based on covering causal paths (Ould-Bouamama and Samantaray, 2008) and is implemented in dedicated software (Chatti et al., 2013; Xiaotian and Anlin, 2014). It is worth mentioning that Djeziri et al. (2007) proposed BG modeling approach in the LFT (Linear Fractional Transformation) configuration that enables to take into account parameter uncertainties. However, it was not able to address the measurements uncertainties. Recently, a new formalism called Signed Bond Graph (SBG) has been proposed to overcome the limitations of the BG and to generate qualitative and quantitative diagnosis on the basis of a single representation (Chatti et al., 2014).

In this paper, an approach that enables to enhance the robustness of the residuals evaluation during the fault detection stage is proposed. It is worth mentioning that different FDI approaches have been developed to address such problem. He et al. (2015) proposed a model-based fault diagnosis approach based on an adaptive extended Kalman Filter (KF) which enables to reduce the measurement noises. However, this approach presents a limitation since it deals only with sensors fault, including the bias fault in current and voltage sensors and gain fault in the voltage

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sensor. Another strategy based on a dedicated Kalman filtering with optimized tuning parameters has been proposed by Gheorghe et al. (2011). The goal of this strategy is to early detect abrupt changes in aircraft control systems by filtering a residual signal emanating from the flight control computer. This strategy has proved its robustness and good performance. However, it was applied to specific faults that can be modeled and it requires an already existing error signal (residual) generation strategy. Recently, Xiong et al. (2013) proposed an extension of conventional Kalman filtering by combining the interval analysis and the statistical behavior of the noise based on the improved Interval KF. The output prediction of the KF is considered as the reference of the healthy system and the standard deviation is used to build the fault detection thresholds. This approach considers bounded parameter uncertainties and centered Gaussian noise and it is used for detecting additive sensor faults. For a comparison between a statistical decision and an interval-based approach, the interested reader can refer to Gelso and Biswas (2008). Another approach has been proposed by Li et al. (2005) where the fault detection is reduced to detecting irregularities in the modeling errors generated by a nonlinear predictive filter. However, this approach requires for the decision step an additional test which is based on statistical features.

Generally, filtering and parameters estimation approaches rely on a statistical hypothesis test such as the Chi-square test (Li et al., 2005). Other FDI approaches proposed in the literature addressed the diagnosis problem by dealing with a set-membership formulation. For example, Tornil-Sin et al. (2012) proposed a robust fault detection strategy formulated as a set-membership state estimation problem, which is implemented by means of constraint satisfaction techniques. Even though this approach enables to take into account both time-variant and time-invariant system models, it requires to know exactly the boundaries of the system's states or to assume that they belong to some a priori known compact set. Both requirements are hard to satisfy in real applications especially when the system's states do not correspond to physical elements within the system.

In threshold-based methods, the presence of abnormal behavior is detected when the residual values exceed a certain prefixed threshold (Touati et al., 2012). A practical difficulty with regard to prefixed thresholds concerns (1) missing detection when the thresholds are too high and (2) false alarms when they are too low. During the last years, a much more attention has been paid to statistical methods in order to address such problem. These methods consider the residual as a random variable and analyze its statistical distribution, such as the Sequential Probability Ratio Test (Kopsaftopoulos et al., 2013). However, statistical methods require to define the statistical distributions of the residuals in faulty situation which can be difficult to obtain in practical industrial applications. Moreover, it appeared that it is more suitable to assume that only bounds on the variables are available rather than assuming a probability distribution for these variables. This is why, various works focused on the so-called set-membership approach which can be used in the context of fault detection (Blesa et al., 2012; Puig, 2010). Recently, various works focused on the design of consistency tests for dynamical systems with additive and multiplicative parameter uncertainties by dealing with intervals analysis (Puig and Montes de Oca, 2013). It is worth noting that most of them were applied for particular classes of non-linear systems such as the so-called flat systems (Jaulin, 2013; Seydou et al., 2013).

As discussed above, it appears clearly that the problem of robust fault detection and isolation in the presence of uncertainties has been addressed in the literature by using statistics and interval approaches. The former ones have represented the uncertainties with Gaussian stochastic variables. However, this assumption is not realistic for real applications since the distribution of the uncertain error is generally unknown. In this paper, the parameters and sensors uncertainties are assumed to be unknown but to stay within known and acceptable bounds. They are also directly incorporated to the ARRs generated on the basis of the SBG. Concerning the existing interval approaches, most of the discussed ones are limited to actuators or sensor faults detection. In the proposed approach, both cases are addressed. Furthermore, the developed approach consists in solving a Constraint Satisfaction Problem (CSP) which does not require a lot of computations at each sampling time, and hence it is compatible with real-time constraints of dynamic complex systems.

In order to detect a fault, a key step has to be well performed namely the residuals evaluation one. The residuals are formed by inputs, measurements, measurements derivatives and system parameters. In order to obtain reliable performances, when evaluating the residuals, all the uncertainties have to be taken into account. Classically, parameters uncertainties have been considered and a strategy was proposed for decoupling the nominal part of a residual from its uncertain one (Djeziri et al., 2007). The nominal part served to evaluate the residual while the uncertain part served to determine the thresholds. A test is then performed in order to check whether the residual belongs to the defined thresholds or not. However, the uncertainties are often uncorrelated. This means that there is a likelihood of them canceling out each other. In addition, the measurements derivatives in the presence of noisy signals can lead to a false alarm problem. This problem is overcome in this paper by using a set membership formulation. Our developed approach consists in solving a Constraint Satisfaction Problem (CSP) which requires to know the derivatives of measured outputs. A numerical differentiator is then proposed to estimate these derivatives while providing their intervals. The CSP solution enables to obtain a contracted interval for each residual. This interval represents the moving horizon residuals enclosures. Finally, an inclusion test is performed in order to check whether zero element belongs to these enclosures or not. The proposed approach is generic since it can be applied to any residual formed by elements and physical phenomena (significant variation of each of them can be directly associated to a fault) that are well defined within the physical model. This is not always the case when dealing with analytical fault detection approaches based mainly on state-space representation such as parity space or filtering approaches since the parameters do not always have a clear physical meaning. Furthermore, the proposed approach is well suited to different kinds of faults i.e. actuator faults as well as parametric and sensor faults.

The rest of the paper is organized as follows. Section 2 recalls some materials and basic notations that are used throughout the paper. Section 3 describes the problem formulation. Section 4 presents the overall developed diagnosis methodology based on the set-membership approach for fault detection. In Section 5, the proposed FDI methodology is applied to an omnidirectional mobile robot. Section 6 concludes the paper by highlighting the strengths of the proposed approach.

2. Preliminaries

This section recalls some basic and useful definitions.

2.1. Bond graph model

A BG is a directed graph $G(S, A)$ whose nodes S represent subsystems, physical components and other basic elements (junctions) while the edges A called power bonds represent the power exchanged between nodes. The exchanged power between