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# Improved diagnosis of hybrid systems using instantaneous sensitivity matrices

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ABSTRACT

One approach to quantitative model-based fault detection and isolation (FDI) is based on analytical redundancy relations (ARRs) and fault signatures. Numerical evaluation of ARRs creates residuals, which then, provide online information of consistency between the system and its nominal model. An inconsistency is represented by a signature. Traditionally in the quantitative approach, these signatures are binary vectors, where the term 0 means a residual is consistent and 1 means inconsistent. In this paper, the measured trend of residuals is utilized for FDI by a different signature type, called sensitivity signature. In this signature, the consistency of ARRs is represented by three terms; the term $+1$ indicates a residual is crossing an upper threshold, the term $-1$ indicates a residual is crossing a lower threshold and 0 means otherwise. The expected sensitivity signature related to a certain fault or to a mode change is taken from partial derivative of residuals. Since consistency, in the sensitivity approach, is represented by three terms (instead of two), more distinguished signatures are generated and improved fault and mode change isolation abilities are achieved. Issues related to practical implementation of the proposed diagnosis method are extensively discussed and experimental results are presented.

## 1. Introduction

Among the many advantages of the bond graph (BG) model, many will consider its ability to represent causal relations between model variables in a clear and systematic way, as one of its major advantages. The ability to effectively analyze causal relations, makes the bond graph an excellent tool for FDI algorithms.

Complex physical systems may consist of different components with different dynamical nature (continuous and discrete). These systems are best modeled as hybrid systems. A hybrid system is represented by a set of modes. In each mode the system is represented by a continuous model and different modes correspond to different continuous models. In hybrid systems, two types of faults can be distinguished, these are, parametric faults and discrete faults. A parametric fault is related to a change of a physical parameter to an unknown abnormal value. On the other hand, discrete faults are due to inconsistency between the expected and the actual mode of the system. Bond graph theory was developed for modeling and analysis of continuous dynamical systems. An extension of this theory to hybrid systems was presented in [1], which has introduced the hybrid bond graphs (HBGs). Fault diagnosis methods, based on the HBG modeling approach, can be found in [2–9].

A fault diagnosis process is divided into three main stages: 1) detection of inconsistency between the behavior of the system and its nominal model, 2) isolation of a set of fault candidates and 3) identification of the true fault and its size. The search for an effective fault isolation method is very important in FDI framework. This effectiveness is measured by the complexity of the algorithm and its

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achieved isolation ability. Improved isolation ability demands, in general, a more complex method and a tradeoff between these two is unavoidable. In model-based process supervision, qualitative methods [10] are considered to be more computationally simple while quantitative methods are considered to be more reliable and provide better isolation ability [11]. In model-based quantitative FDI methods, analytical redundancy relations (ARRs) are derived systematically from the systems model [12,13]. These model-based quantitative methods require online evaluation of ARRs, and the performance of the method depends on the quality model. Nevertheless, recent development of powerful micro-computers and the fact that an accurate model can be derived for many industrial applications make the model-based quantitative FDI methods attractive and feasible.

A numerical evaluation of an ARR generates a residual. In fault-free conditions, the residual value is theoretically zero. The residual value is nonzero in the presence of a fault, if the residual is sensitive to the occurred fault. An inconsistency is often detected by a threshold-based rule, such as |residual| > threshold, where the threshold can be a predetermined constant value [4,5,14–17] or an adaptive threshold with a time varying value [18–20]. A coherence vector is utilized to represent the fault signature; its standard form is $CV = [cv_1 cv_2 .. \ cv_r]^T$ where $cv_i \in \{0, 1\}$ is a binary variable representing the consistency of GARR$_i$ (0 if it is consistent and 1 otherwise). The expected signature due to a certain fault is derived a priory and all possible signatures are presented in a matrix, known as the fault signature matrix (FSM) (or global FSM if the system is hybrid [4]). Fault diagnosis methods based on this strategy do not use important information hidden in residual trends. In this paper, residual trends are taken into account; a strategy which leads to a coherence vector of the form $CV = [cv_1 cv_2 .. cv_r]^T$, where $cv_i \in \{0, +1, -1\}$. The sign $+1$ indicates a residual is crossing an upper threshold while the sign $-1$ represents the opposite, namely, crossing a lower threshold; the sign 0 represents consistency. This coherence vector is richer in information and therefore improves fault and mode-change isolation. It is clear that more unique signatures can be generated from a set of $r$ redundancy relations; the maximum number of unique signatures is now $3^r$, compared to $2^r$ achieved from the standard binary representation. In a hybrid system diagnosis framework, the coherence vector expresses consistency of both parametric faults and modes. An inconsistency may indicate an unexpected mode change, for instance, due to a discrete fault. Mode tracking and discrete fault isolation is based on the mode change signature and all possible mode change signatures are represented in a matrix, named, mode change signature matrix (MCSM) [4]. This matrix, and the global FSM (GFSM) are derived offline from the HBG and represent cause–effect relations between parametric faults, mode changes and residuals. These two matrices are redefined in this paper in order to include the new form of expected signatures.

To date, the trend of residuals was never exploited for improvement of isolation abilities in model-based quantitative FDI methods. On the other hand, the trend of abnormal measurements is the essence of well known qualitative methods [9]. These methods are based on models in which the parameters are unknown or uncertain and thus only their qualitative values or qualitative states are considered; where, increasing means higher than normal, decreasing is lower than normal, and normal refers to an unchanged value [21]. Fault isolation and validation is based on backward and forward propagation of qualitative values along causal trajectories [22].

In this paper, the expected residual trend due to a fault or due to a mode change is generated by explicit partial derivative of residuals. This information is presented in two signature matrices, which in general are time varying and replace the GFSM and the MCSM in their standard form. Instead of explicit partial derivatives, sensitivity information of residuals can be derived by utilizing unique BG based numerical approaches, such as the sensitivity BG (SBG) [23,24] or the incremental BG [25–27]. These numerical approaches are more important in applications where the derivation of analytical residuals is not possible, e.g., due to algebraic loops. If an explicit representation of ARRs is not achievable, the diagnostic BG approach of [17] can be used, which has been shown to be extendable to the concept of SBG in [28] and to diagnosis of hybrid systems in [2]. The fault isolation process described in this paper is based on the single fault assumption. Although the multiple fault isolation problem is not discussed here, it is clear that improved fault isolation ability may be achieved also for the multiple fault case.

Model uncertainty, process disturbances and measurement noise are common real life difficulties that may cause a model based FDI technique to be hard for implementation or inefficient. If the intensity of disturbances and noise is reasonable, these problems can be remedied by the proper choice of residual thresholds. In some cases, constant thresholds can be applied with minimum false alarms and misdetections, and if large threshold values are required due to high level of uncertainty, adaptive threshold algorithms such as [18–20] may be applied. However, since residual computation involves time derivatives of measurements which could be highly noisy, effective filtering techniques are necessary. This problem is considered in this paper and a solution is proposed in the form of residual filtering. Two implementation approaches of residual filtering are proposed here. One approach assumes that the residuals may be given explicitly in a closed-form expression and thus the filtering may be implemented explicitly. The other approach assumes that a closed-form expression of the residuals is not given and thus the filtering is implemented implicitly by an extended bond graph diagnostic model. The later approach (that is more related to numerical generation of residuals) allows a uniform description of filtered residuals that completely lies in the bond graph framework.

The description of the diagnosis method described in this paper is supported by numerical examples and experimental results. The paper is organized as follows. Section 2 reviews the diagnostic HBG modeling approach. Section 3 presents the concept of sensitivity signatures and sensitivity signature matrices. Section 4 presents an example and numerical results for a theoretic case study. Section 5 presents the suggested algorithms for residual filtering and section 6 describes a practical example of the methods on experimental testbed. Section 7 concludes the paper.

## 2. Hybrid modeling for fault diagnosis

Analytical redundancy relations represent constraints between known process variables. The real time evaluation of ARRs generates residuals, which indicate on consistency between the system and its nominal model. ARRs can be derived systematically from a