Engineering Applications of Artificial Intelligence 59 (2017) 51–72

Contents lists available at ScienceDirect

Engineering Applications of Artificial Intelligence

journal homepage: www.elsevier.com/locate/engappai

Real time algorithm based on time series data abstraction and hybrid bond graph model for diagnosis of switched system

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ARTICLE INFO

Keywords:
Switched System
Hybrid Bond Graph
Qualitative Diagnosis
Parametrized Temporal Causal Graph
Piecewise Aggregate Approximation
Page-Hinkley Test

ABSTRACT

In this paper, we propose a real time algorithm to realize a diagnosis of switched systems for abrupt parametric faults. This algorithm is based on interaction between a Qualitative Diagnosis (QD) and a monitoring component that performs a Qualitative Trend Analysis (QTA) of residual signals generated from Bond Graph (BG) elements called residual sinks. The QTA is applied in order to on-line detect change in the mean of residual signal based on combination of Piecewise Aggregate Approximation (PAA) with Page-Hinkley Test (PHT). The QD procedure is performed in two stages. In the first off-line stage, Symbolic Fault Signature Matrix (SFSM) is generated from a Parameterized Temporal Causal Graph (PTCG). The PTCG is valid for all system modes and deduced from a unified Hybrid Bond Graph (HBG) model by converting its elements into node and labeled edge. Each entry in the SFSM matrix gives the residual symbolic signature which corresponds to the lower-order signature predicted using the PTCG model by propagating initial deviation from the fault parameter in the label of edge to the residual node. In the second on-line stage, trend extraction by linear regression is triggered after change detection in order to estimate the lower order time-derivative symbol for each residual sinks. Subsequently, we propose a stepwise similarity measure for fault isolation task. The functioning of this approach is illustrated in simulating with a switched quarter-car active suspension system.

1. Introduction

Physical systems with switching are termed hybrid dynamic systems (Kypuros, 2001). Moreover, switches are physical mechanisms that discontinuously redirect the flow of power in a system. Semiconductor switches, hydraulic valves and mechanical clutches are example of switched elements mechanisms. When switching occurs, the system may change its mode of operation and system with n switching states has 2^n possible operating modes. Consequently, systems that employ physically switched elements are difficult to model. As the complexity of systems increases, Fault Detection and Isolation (FDI) become more important since it is an essential means to maintain system safety and reliability. Typically, fault diagnosis includes three tasks: fault detection, fault isolation and fault identification (Gertler, 1998; Chiang et al., 2001; Precup et al., 2015; Isermann, 2009; Ding, 2008; Korbicz et al., 2004). For fault detection task, residual-based approach has attracted much attention (Niu et al., 2015; Serdio et al., 2014a; Borutzky, 2009a; Staroswiecki and Comtet-Verga, 2001). It consists in the generation and evaluation of diagnostic signals called residuals. Depending upon the knowledge (model-based or data-driven) used and the nature of information processing (quantitative or qualitative) various techniques can be applied to generate residuals and evaluate them. However, the design of a residual-based approach should be adapted when we deal with a switching behavior within system dynamic. In fact, due to change in the operating mode of the switched system, time series of measurement exhibits singularities features even when no faults are present in the system. Recently, a data-driven fault detection (FD) tool is presented in (Serdio et al., 2014a, 2014b) and extended in (Serdio et al., 2015) by integrating a fault isolation (FI) level based on gradient and quality information. In the FD framework, residuals are obtained through data-oriented system identification (SysId) models. The particularity of this framework is its ability to resolve the singularities, in measurements, by transforming the original time-amplitude space into a reduced dimensional product-amplitude space (also called “residual space”) over a different set of measurements. While the SysId models are given under several forms (including linear, nonlinear and fuzzy models), the proposed framework is only well suited for sensors and actuators FDI. In order to isolate parametric faults, as it is our purpose in this work, more *a priori* knowledge is needed to have properly structured residuals. Among several residual generation methods that have been developed, Analytical Redundancy Relation (ARR) provides the possi-

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http://dx.doi.org/10.1016/j.engappai.2016.12.009
Received 14 December 2015; Received in revised form 17 August 2016; Accepted 5 December 2016
0952-1976/

bility to have such structured property. That is, ARR correspond to relations between system variables which can be explained from the physical model and defined under symbolic or numeric form (Staroswiecki and Comtet-Verga, 2001; Ding, 2008). Moreover, ARR can be easily generated from graphical models that are commonly used to describe complex systems such as causal graphs, bipartite graphs and bond graphs (Yang et al., 2014). Compared to other graphical model, the causal properties of the Bond Graph (BG) provide more detailed information that allows the FDI algorithm to isolate a fault at component level easily (Ould Bouamama et al., 2014; Borutzky, 2009b). BG is based on analyzing the flow of energy, which is the product of a *flow* variable and an *effort* variable, through the interconnections of components called ports (Karnopp et al., 2000). The flow of energy between ports is shown by a line, which is called bond. When two elements are interconnected, there are power interactions between them. The power can be in different forms: mechanical, electrical, hydraulic or thermal. Power is product of two variables called power variables; e. g. mechanical power is the product of force (*effort*) and velocity (*flow*), whereas hydraulic power is the product of pressure (*effort*) and flow rate (*flow*). In BG model, any physical system (or subsystem) can be described by elementary components which include source elements *Se* and *Sf*, dissipative element *R*, storage elements *C* and *I*, two junctions 0 and 1, and two transformers *TF* and *GY* (Karnopp et al., 2000; Kypuros, 2013). As BG modeling is based on the exchange of energy between components, the methodology was initially used to capture continuous time phenomena. Extensions that also cover hybrid system models have been reported in the literature (Dauphin-Tanguy and Rombaut, 1989; Strömberg et al., 1993; Mosterman and Biswas, 2000; Umarikar and Umanand, 2005). Modeling of hybrid systems using a BG is one of the topics of research and various models have been proposed (Borutzky, 2009a; Pulido and Alonso-Gonzlez, 2004; Mosterman and Biswas, 1999; Manders et al., 2000; Narasimhan, 2002). To include discrete transition and modeling switching phenomena, additional mechanisms are introduced into the continuous BG language. In this work we adopt the concept of Hybrid Bond Graph (HBG) proposed by (Mosterman and Biswas, 2000), which extends the ability of BG to model hybrid systems using controlled junctions. Each controlled junction has two possible states, ON or OFF, which corresponds to an active or an inactive junction. Therefore, a controlled 1-junction is used to inhibit *flow* and a controlled 0-junction is used to inhibit *effort*. The concept of controlled junctions is an intuitive representation for structural discontinuities because they show clearly where elements connect and disconnect and break the path of power flow (Rebecca et al., 2013). Those junction switching function are implemented as a finite state automaton control specification. The finite state automaton may have several states, and each state maps to either the OFF mode or the ON mode of the junction. Modes transition expressed only by external controller signals define controlled switching, and those expressed by internal variables crossing boundary values define autonomous switching. The overall mode of the system is determined by a parallel composition of modes of the individual switched junctions.

2. Switched systems modeling and diagnosis

HBG is a BG-based modeling approach which provides an effective tool not only for dynamic modeling but also for FDI of switching systems (Borutzky, 2012; Low et al., 2010a). BG has been proven useful for FDI for continuous systems (Borutzky, 2009a; Pulido and Alonso-Gonzlez, 2004; Mosterman and Biswas, 1999; Manders et al., 2000; Samantaray et al., 2006). In these model-based approaches, modeling has been used for both qualitative and quantitative FDI. The general principle of these BG model-based FDI approaches is to compare the expected behavior of the system, given by model, with its actual behavior. The first step of a FDI procedure consists in generating a set of residuals which reflect the discrepancy between the two behaviors.

2.1. Quantitative approaches for FDI of switched systems

In the quantitative FDI approaches, ARR methods are classically used for residual generation (Borutzky, 2009a; Low et al., 2010a). ARRs are static or dynamic constraints which link the time evolution of known (i.e. parameters, inputs and measurements) variables when the system operates according to its normal operation model. ARRs have to be sensitive to faults and insensitive to perturbations. ARRs are derived from the set of over-determined equations obtained from the structural system model. In the BG framework, this translates to first generating equations that correspond to the conservation laws at each 0− and 1−junction, and manipulating these equations till only known variables remains. A concept of Global Analytical Redundancy Relation (GARR) has been proposed to extend the ARR based fault for switched dynamic systems (Low et al., 2010b). Aiming at a set of ARRs that holds for all system modes, authors in (Low et al., 2008) study the computational causality effects controlled junctions have on adjacent parts of the BG under alternative causality assignments and propose a modification of the Sequential Causality Assignment Procedure (SCAP). The main goal of the so-called Sequential Causality Assignment Procedure for Hybrid System (SCAPH) was to assign the HBG a desirable causality that facilitates analysis and FDI designs by introducing a Boolean variable to model the eliminations of *flow* or *effort* variables due to the OFF states of the controlled junctions. Fig. 1 shows the flowchart of the SCAPH procedure and the summary of the algorithm to derive the Diagnostic Hybrid Bond Graph.

In model-based FDI for switched dynamic systems, GARRs are HBG-based method for symbolic residual generation. However, as for continuous dynamic systems, this method requires high computational costs for equation derivation and can not be applied when unknown variables can not be eliminated because of the presence of algebraic loops and non-linear non-invertible constraints (Borutzky, 2009a, 2012; Samantaray et al., 2006). As solution to these problems, author in (Borutzky, 2009a, 2012) proposed additional BG element termed as “residual sinks” used for a numerical computation of the residuals without having to derive ARRs in symbolic form. In contrast to another proposed method (Samantaray et al., 2006) where sensor variables are represented as sub-graph coupled to a Diagnosis Bond Graph model with preferred derivative causality, residual bond graph sinks use integral causality as the preferred computational causality in BG model. Fig. 2 gives a representation of *residual effort sink* and *residual flow sink* denoted as *rSe* and *rSf*, respectively.

For both, the difference (Δe and Δf) between the measured variable obtained from sensor in real process and the output of the normal behavior BG-model is fed into modulated sinks that deliver the residual signal *res*. As shown in Fig. 2, these outputs from the residual sinks, denoted *res*, become additional inputs to the BG-model that alter its normal behavior until the difference (Δe and Δf) vanishes.

2.2. Qualitative approaches for FDI of switched systems

In qualitative FDI approaches, methods such as possible conflicts (Pulido and Alonso-Gonzlez, 2004), and analysis of Temporal Causal Graphs (TCG) (Mosterman and Biswas, 1999) has developed for diagnosis of systems. These methods are based on the structural analysis of dynamic models. For example, authors in (Mosterman and Biswas, 1999) developed a diagnosis schema, which called TRANSCEND, based on the qualitative analysis of fault transient