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Fault detection, isolation and identification for hybrid systems with unknown mode changes and fault patterns

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ABSTRACT

This article presents a solution to the problem of multiple fault detection, isolation and identification for hybrid systems without information on mode change and fault patterns. Multiple faults of different patterns are considered in a complex hybrid system and these faults can happen either in a detectable mode or in a non-detectable mode. A method for multiple fault isolation is introduced for situation of lacking information on fault pattern and mode change. The nature of faults in a monitored system can be classified as abrupt faults and incipient faults. Under abrupt fault assumption, i.e. constant values for fault parameters, fault identification is inappropriate to handle cases related to incipient fault. Without information on fault nature, it is difficult to achieve fault estimation. Situation is further complicated when mode change is unknown after fault occurrence. In this work, fault pattern is represented by a binary vector to reduce computational complexity of fault identification. Mode change is parameterized as a discontinuous function. Based on these new representations, a multiple hybrid differential evolution algorithm is developed to identify fault pattern vector, abrupt fault parameter/incipient fault dynamic coefficient, and mode change indexes. Simulation and experiment results are reported to validate the proposed method.

1. Introduction

As the complexity of industrial systems increases, fault detection and isolation (FDI) becomes more important since it is an essential means to maintain system safety and reliability. The capability of detecting a fault quickly after fault occurrence enables us to take corrective actions in a timely manner and avoid catastrophic consequences. In general, the nature of faults can be classified as two categories: abrupt faults and incipient faults. Abrupt faults are usually modeled as instantaneous changes in system parameters and lead to distinct inconsistency in the monitored system. Incipient faults usually describe the wear and ageing of system components and thus are relatively difficult to handle due to the slowly developing nature of these faults.

Generally, fault diagnosis includes three tasks: fault detection, fault isolation and fault identification. Fault detection aims to indicate the occurrence of a fault once it happens; fault isolation tries to locate the fault; and fault identification is to estimate the size of the fault (Blanke, Kinnaert, Lunze, & Staroswiecki, 2003). Model based fault diagnosis is based on residuals that provide a measure of deviation between the behavior model and monitored system. A fault is declared if the absolute value of residual exceeds a predetermined threshold. The performance of model based FDI depends on the quality of the model. Bond Graph (BG) provides a tool to model complex system involving various energy domains in a unified framework. In BG model, all system components and system structure are clearly presented on the graph which contributes to fault isolation. In recent years, BG based FDI has been successfully applied to different engineering fields, such as mobile robot (Arogeti, Wang, & Yu, 2009), air conditioning systems (Ghiaus, 1999), and industrial steam generator (Ould-Bouamama, Medjaher, Samantaray, & Staroswiecki, 2006), etc.

Hybrid systems involve continuous state evolution within a mode and discrete transitions from one mode to another. For each mode, the system follows a dynamics that is different from that of other modes. Mosterman and Biswas (1995) developed Hybrid Bond Graph (HBG) to include the notion of idealized controlled junctions and thus represent hybrid systems in a compact manner. Fault diagnosis for hybrid systems requires both information of continuous states and discrete mode evolution. The main difficulty when considering model based FDI for hybrid systems is due to unknown mode changes. There are several works concerning hybrid system diagnosis. In Cocquempot, Elmezyani, and Staroswiecki (2004), the FDI process of a hybrid system is based on analytical redundancy relations (ARRs), and the model is a hybrid automaton. Faults are

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detected by a mode-tracking technique, based on residuals consistency and discrete dynamical model. In Wang, Li, Zhou, and Liu (2007), a model-based mode identification approach is proposed, where a bank of N continuous observers (each represents a suspected system's mode) is employed simultaneously in a hybrid system estimation framework. In Narasimhan (2002), the HBG is used to develop a quality-quantitative diagnosis framework for hybrid system with abrupt parametric fault. The fault detection is based on a hybrid observer. A Finite State Machine is used to determine the new mode. When the data is collected for fault identification, the mode is assumed to be persistent.

Recently, a new concept of Global Analytical Redundancy Relations (GARRs) has been proposed to extend the Analytical Redundancy Relations (ARRs)-based fault diagnosis for hybrid systems (Low, Wang, Arogeti, & Luo, 2010; Low, Wang, Arogeti, & Zhang, 2010). GARRs describe the behavior of a hybrid system at all operating modes and they are derived systematically from the hybrid Bond Graph model of a hybrid system. In Arogeti, Wang, Low, Zhang, and Zhou (2008), mode tracking in normal conditions and fault detection and isolation is presented. These works use single fault assumption, and if a new mode is not identified by the ARR based mode identification (i.e., narrowed and full), then the conclusion is that the GARR event (which had triggered the mode identification process) is due to a parametric-fault, and the combinational effect of both mode changes and faults which initiate at a non-detectable and are followed by a detectable mode on GARRs is not concerned. A method of simultaneous identification of fault parameters and mode switching stamps for hybrid systems is proposed in Yu, Luo, Arogeti, Wang, and Zhang (2010), in which a unified formula is developed to cater for difficult situation where mode change occurs after fault occurrence. This method focuses on single abrupt parametric fault which happens at a detectable mode.

Hybrid system monitoring needs estimation of continuous states and prediction of the system mode evolution. When mode evolution of a hybrid system is known, health monitoring of such a system is easy because the knowledge of the mode at any moment is available. However, lack of mode information will make it difficult to carry out a health monitoring scheme. In addition, fault pattern information is important for fault identification. Most existing techniques of FDI in the literatures are designed for systems with only abrupt faults or with only incipient faults and few works concerning systems with abrupt faults and incipient faults occurring simultaneously are reported. A real complex system consists of many components, and a method capable of adapting to handle multiple faults of different nature can provide more advantages.

This paper addresses FDI and multiple fault estimation for hybrid systems with unknown fault pattern and mode changes. The fault could be abrupt fault or incipient fault and unknown in advance. The mode tracker is employed to estimate the mode before fault occurrence. By a suitable transformation, the fault pattern of fault candidates is represented by a binary vector to avoid exhaust search during identification process. The faults under consideration may happen at all modes, i.e. detectable modes and non-detectable modes. Once a fault is detected, a hypothesis set which includes both suspected faults and suspected mode changes is established. A multiple hybrid differential evolution (MHDE) algorithm is proposed for fault identification. In MHDE, each hybrid differential evolution estimator is utilized to identify the abrupt fault parameter/incipient fault dynamic coefficient and mode change indexes for one element in the set of fault candidates. A fault pattern selection scheme is embedded in the estimation process. All hybrid differential evolution estimators run in parallel to determine the true faults with correct pattern.

This paper is organized as follows: Section 2 introduces the concept of Augmented GARRs (AGARRs) and the mode tracking technique. Section 3 discusses the multiple fault isolation without mode change and fault pattern information. The MHDE algorithm for multiple fault identification is also addressed. Section 4 illustrates an example with multiple faults of unknown pattern and mode change. Simulation and experiment of different fault scenarios are carried out to verify the proposed methodology. Finally, concluding remarks are given in Section 5.

2. AGARRs and mode tracking technique

2.1. AGARRs for fault diagnosis

The performance of model based FDI primarily depends on model accuracy (Samantaray & Ould-Bouamama, 2008). Because of the multidisciplinary nature of most industrial processes (mechanical, hydraulic, electrical, etc.), a unified modeling of a physical system is a critical step (Luo, Wang, & Pham, 2005). Bond Graph (BG) provides an efficient tool to model complex systems and allows both structural and behavioral system analysis (Karnopp, Margolis, & Rosenberg, 2006). BG is a pictorial representation of systems with complex energy interactions and it is based on energy conservation principle. For each bond, there are two energy variables, effort and flow, to describe the states of the physical components. Depending on the type of system, effort can represent voltage, force, torque or pressure, while flow can represent velocity, volume flow rate, current, or entropy flow rate. The bonds are numbered and the power variables correspond to the number of the bond. In recent years, BG modeling has been successfully applied to model various process engineering systems. Furthermore, BG based techniques have been developed for the analysis of structural control properties, fault diagnosis, sensor placement (Samantaray, Medjaher, Ould-Bouamama, Staroswiecki, & Dauphin-Tanguy, 2004), parameter estimation (Low, Wang, Arogeti, & Luo, 2009) and model order reduction. BG modeling is developed for modeling continuous systems, while it cannot be applied to model directly. In order to model discrete mode change of a hybrid system, HBG expands the modeling capability of BG to include controlled junctions. In this way, a hybrid system can be represented by BG components in a concise manner. For the 1 controlled junction, it enforces zero flow to all connected bonds when it is turned off; similarly, the 0 controlled junction forces the effort value to zero at all connected bonds during the OFF state.

Model based FDI procedures utilize structural analysis to eliminate the unknown variables to generate the constraints called analytical redundancy relations (ARRs). Numerical evaluation of ARRs produces residuals. The residuals characterize the system operating condition, close to zero in normal operation and distinct from zero when a fault occurs. From the ARRs, the Fault Signature Matrix (FSM) can be deduced. The FSM can be used for online fault isolation as well as offline monitoring ability analysis. When compared with observer based residuals, ARRs based residuals have some advantages: such as easy to understand, since they represent relations between system variables from the physical model; and simple to formulate, because they can be defined in symbolic form.

A simple ARRs derivation method for a hybrid system is to consider each mode individually. This method is not efficient and does not cater for the unique representation of the HBG. In order to achieve a more efficient way, a set of unified constraint, called Global Analytical Redundancy Relations (GARRs), is developed to describe the behavior of a hybrid system at all modes (Low, Wang, Arogeti, & Luo, 2010). In general, GARR equations take the following form

$$g_l(\theta, \alpha, De, Df, u) = 0 \quad \text{for} \quad l = 1, 2, \ldots, m \tag{1}$$

where m denotes the number of GARRs derived from the HBG; $\theta = [\theta_1, \theta_2, \ldots, \theta_m]^T$ represents the nominal parameters of the