Available online at www.sciencedirect.com

SCIENCE DIRECT®

Simulation Modelling Practice and Theory 14 (2006) 237–262

SIMULATION MODELLING PRACTICE AND THEORY

www.elsevier.com/locate/simpat

Diagnostic bond graphs for online fault detection and isolation

A.K. Samantaray [a,*], K. Medjaher [b], B. Ould Bouamama [b], M. Staroswiecki [c], G. Dauphin-Tanguy [d]

[a] *Department of Mechanical Engineering, Indian Institute of Technology, 721 302 Kharagpur, India*
[b] *LAGIS, CNRS UMR 8146, University of Lille-1, Cité Scientifique, 59655 Villeneuve d'Ascq Cedex, France*
[c] *Ecole Polytechnique Universitaire de Lille, University of Lille, 59655 Villeneuve d'Ascq Cedex, France*
[d] *LAGIS, CNRS UMR 8146, Ecole Centrale de Lille, BP48 59651, France*

Received 29 January 2004; received in revised form 29 March 2005; accepted 31 May 2005
Available online 11 July 2005

Abstract

Analytical redundancy relations (ARR) are symbolic equations representing constraints between different known process variables (parameters, measurements and sources). ARR are obtained from the behavioural model of the system through different procedures of elimination of unknown variables. Numerical evaluation of each ARR is called a residual, which is used in model based fault detection and isolation (FDI) algorithms. For processes and systems with complex non-linearity, eliminating all unknown variables is not trivial, e.g. in the presence of algebraic loops, implicit equations, non-invertible functions, etc. However, most symbolically non-resolvable relationships can be numerically solved; and then, it becomes possible to maximise the number of structurally independent residuals. Bond graph modelling is used in this paper to derive ARR and to obtain the computational model in the case of non-resolvability of equations. A set of sub-graph substitutions in the bond graph model are developed. These substitutions directly lead to a form, where known variables (measurements, sources and parameters) are the inputs and the residuals are the outputs. Such a model is then called a diagnostic bond graph (DBG) model. It is shown that DBG models can be used for online residual computation as well as for offline verification using process data from a database. A

* Corresponding author. Tel.: +91 3222 282998/282999; fax: +91 3222 282278.
E-mail address: samantaray@lycos.com (A.K. Samantaray).

1569-190X/$ - see front matter
doi:10.1016/j.simpat.2005.05.003

method for the coupling of the bond graph model, used to generate the residuals, with a bond graph model, used to describe the process behaviour, is presented. The coupled model allows simulation of process behaviour both in the presence and in the absence of the faults, which is consequently used to obtain residual responses and validate the fault signatures.

Keywords: Analytical redundancy; Diagnostic bond graph; Residual; Fault detection and isolation

1. Introduction

Fault detection and isolation (FDI) procedures implemented in the industrial supervision platforms consist of the comparison between the actual behaviour of a system and its reference behaviour. Different approaches for the FDI have been developed, depending on the kind of knowledge used to describe the process model. A good account of these up to 1996 is given in [1], and up to 2003 is given in [2–4]. FDI methods can be broadly categorised into two groups, namely, model based and non-model based. Model based FDI methods require a mathematical model representing the behaviour of the system. However, modelling is an important and difficult step because of the complexity of the monitored system along with its control equipment. Bond graph modelling [5–8], as a unified multi-energy domain modelling method, is especially suitable for developing models of process engineering systems [9]. Bond graph modelling has also been used in the past for different FDI approaches [10–14]. Moreover, the structural control properties (controllability, observability, etc.) can be deduced by graphically analysing the causalities (cause and effect relationships) on a bond graph model [15]. These properties have been already used to optimise sensor placements and determine hardware redundancies [16]. Analysis of causal paths [17–19] can identify problems in formulation of the model equations and also problems that one may face in numerical evaluations. Furthermore, causal properties of the bond graph model have been used to determine the origin and the consequences of the faults [12,16].

A model based FDI procedure works by evaluating physical constraint laws using sensor data and parameter values from the monitored system. Analytical redundancy relations (ARR) and observer based approaches are the most widely used model based FDI approaches [20–23]. ARR represent constraints between different known variables (parameters, measurements and sources) in the process. In other words, ARR are static or dynamic constraints which link the time evolution of the known variables when the system operates according to its normal operation model. Once ARR are designed, the fault detection (FD) procedure checks at each time whether they are satisfied or not, and when not, the fault isolation (FI) procedure identifies the system component(s) which is (are) to be suspected. For the FDI procedure to work properly, ARR should be structured, sensitive to faults and robust, i.e. insensitive to unknown inputs and disturbances.

Analytical redundancy relations are obtained from the behavioural model through different procedures of elimination of unknown variables (e.g. parity space