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On-line robust graphical diagnoser for hybrid dynamical systems

Ibrahim Abdallah *, Anne-Lise Gehin, Belkacem Ould Bouamama

Univ. Lille, CNRS, Centrale Lille, UMR 9189-CRIStAL—Centre de Recherche en Informatique Signal et Automatique de Lille, F-59000 Lille, France

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ABSTRACT

This paper proposes a generic tool named Hybrid Bond Graph (HBG) driven by an automaton. Along with the conventional Bond Graph (BG) properties, the proposed approach offers some very valuable advantages in modelling the Hybrid Dynamical Systems (HDS). It allows having one global model of all the distinct dynamics called dynamical operating modes generated due to the hybrid aspect of the system. Compared with other classical approaches such as the hybrid automata, the Operating Mode Management (OMM) is much simpler and more effective thanks to the separation between the continuous dynamics associated with the BG continuous state and the discrete state governed by a separate classical automaton. From the diagnosis point of view, the approach allows to obtain one global graphical robust diagnoser simply derived from the model using the Linear Fractional Transformation (LFT). Using the BG causal properties along with the correspondences between the system components and the BG elements, the Event-Driven Hybrid Bond Graph (EDHBG) also helps to associate between the faults and their suspected components. The innovative interest in this work is that it allows for a non-expert user to perform the modelling, the on-line robust diagnosis and the OMM, without expressing the algebraic equations of the system and regardless of its hybrid aspect. A pedagogic experimental set-up serving as a comprehensive example is implemented on 20Sim[1] to demonstrate the potential of this technique.

0. Introduction

For any given dynamical system many tasks, such as the control, the Model-Based Diagnosis (MBD), the sizing studies and the design, rest on finding the proper dynamical model. In general, the dynamical systems are mainly divided into discrete and continuous systems. For each class different modelling frameworks are introduced: such as the Grafcet, Petri Net, Automata (Hrúz and Zhou, 2007; Sogbohossou and Vianou, 2015; Cabral et al., 2015) for the discrete systems, and the transfer function, the State–Space Equations (SSE) and the BG for the continuous systems. However, both fields do not cover all the existing dynamical behaviours. Systems such as the HDS, because of their dual continuous–discrete aspect, are very difficult to be interpreted as fully continuous nor as only discrete. The existing modelling methods and the MBD approach tend to use multi-models or/and heterogeneous graphical–analytical approaches to deal with the HDS. In such methods, in order to derive an appropriate model to apply the MBD, an engineer needs profound knowledge in all the related fields along with all the different operating modes of the hybrid dynamics. This can be very exhausting and time-consuming for large systems. Nowadays, thanks to the development of softwares that are compatible with the BG modelling such as 20Sim[1] and 20Sim 4C[1], a fast graphical dynamical modelling is made possible and easy.

This paper proposes a well-adapted graphical modelling tool for the HDS using a HBG driven by an automaton. The graphical model can be easily modified to perform a robust MBD.

The proposed tool contributes in simplifying three essential tasks: the modelling, the MBD and the OMM. Indeed, some analytical approaches already exist allowing to perform a robust MBD of the uncertain continuous and the HDS. In those methods, the HBG representation is used to drive a set of algebraic analytical equations for the diagnosis (Borutzky, 2012, 2015; Low et al., 2010; Ghoshal et al., 2012; Low et al., 2010; Ould-Bouamama et al., 2012; Bouamama et al., 2014). However, this is not in accordance with the genuine idea that offers the BG as a graphical tool and results in the loss of all the benefits of an abstract energetic and multi-physical tool of modelling. In the present work, the BG theory is expended from just the graphical modelling framework to cover the robust diagnosis replacing the classical analytical approach. The graphical-causal aspect of the BG offers a powerful feature that

[1] BG friendly modelling software; www.20sim.com.

* Corresponding author.
E-mail addresses: ibrahim.ab.abdallah@hotmail.com (I. Abdallah), anne-lise.gehin@univ-lille1.fr (A.-L. Gehin), belkacem.ouldbouamama@polytech-lille.fr (B. Ould Bouamama).

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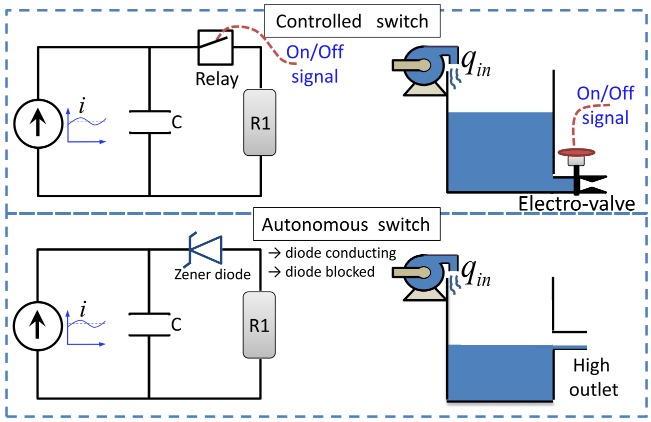

Fig. 1. HDS with controlled switches and autonomous switches.

allows the association between the modelling parameters to their related physical components.

This paper is divided into four main parts. Part I deals with the HDS modelling and introduces the proposed modelling approach called the EDHBG. Part II addresses the MBD diagnosis of the HDS, it shows how the proposed EDHBG allows the implementation of an on-line graphical diagnoser. In the third part III, the graphical HBG diagnoser is extended using LFT-HBG to include the uncertainties allowing an on-line robust diagnosis. Along these three parts, a simple hydraulic system is used as a pedagogic example to elaborate the models and the diagnosers. In part IV, the results of the modelling and the diagnosis are illustrated for the given application. Part IV presents the general conclusion.

1. Hybrid Dynamical Systems

1.1. General context

The HDS are encountered in various domains (electrical, chemical, hydraulic, etc.) (Van Der Schaft and Schumacher, 2000). They are characterized by their dynamics that evolve, in both, continuous and discrete behaviours. This is due to the spontaneous transitions from one state to another one in the dynamic behaviour, each dynamical state is referred to as an "Operating Mode (OM)".

Mathematically, this implies that the dynamical behaviour, which is often expressed by the SSE, does not always conserve the same Ordinary Differential Equations (ODE) or/and the same variables. Depending on the nature of the discrete phenomena, HDS can be classified into different sub-categories such as the switching systems, the jump linear systems, the mixed logical dynamical systems (Heemels et al., 2001; Engell et al., 2003).

In this work, we focus our interest on the switching systems which represent a wide class of the HDS. Such systems contain power switches, each one is characterized by its discrete dual-state (active/inactive). According to the nature of the transition conditions that trigger the switching states, two kinds of switches can be distinguished. Controlled switches (e.g. electrical switch, valve) are controlled by an external signal (as a control input). Autonomous switches depend on the inner conditions of the system such as the state variable (e.g case of the diode) see Fig. 1. In order to model the HDS, the conditions that drive the discrete states of the switches must be known or evaluable.

1.2. Modelling Hybrid Dynamical Systems

Any hybrid dynamical model needs to take into account the parallel evolution of the continuous state along with the revolution of the discrete states of the system. Finding the convenient tool to model the HDS is still an active research topic (Sayed Mouchaweh, 2016; Bertrand et al., 2015; Borutzky, 2015; Ghomri and Hassane, 2015; Gao et al., 2015), HDS modelling approaches rely on state-event-graphs representation inherited from the Discrete Event System (DES) literature. They express the discrete state by boolean firing expressions which define the conditions to switch between the different dynamics i.e from one OM to another one. In each mode, the dynamic evolves continuously with respect to a given set of continuous differential equations (Alur et al., 1995; Lygeros et al., 2003). The main existing approaches are: Hybrid Automaton (HA) (Alur et al., 1995; Lygeros et al., 2003; Bertrand et al., 2015; Schwarze et al., 2013; Goebel et al., 2009), Hybrid Petri Net (HPN) (Rene and Hassane, 2005; Valentin and Rimlinger, 2002; Bertrand et al., 2015; Ghomri and Hassane, 2015; Alla and Ghomri, 2012), Hybrid Grafcet, Statechart (Harel, 1987; Kesten and Pnueli, 1992). Other methods are inherited from the continuous systems modelling approaches such as Hamiltonian port (van der Schaft and Jeltsema, 2014; Haddad et al., 2003) and HBG. In all these modelling approaches, except the HBG, the explicit analytic equations of the system model must be found and written for each mode aside. This can be manageable for few modes, however, when dealing with large complex systems with many modes this can be a very hard and time-consuming task. In order to investigate the different approaches, we compare two formalisms: the Hybrid Automaton and the HBG. The two approaches are, then, applied on a hydraulic system.

1.2.1. Hybrid Automaton

Hybrid Automata are extended from the classical automaton used for modelling the discrete systems. As a mixed representation, they consist of an oriented graph for the discrete behaviour with its modes and an algebraic representation of the continuous dynamic. In each mode, the associated dynamic is expressed by the analytical SSE Fig. 6. With only one activated mode at the time, this implies the HA must be deterministic. Many softwares such as Matlab are able to model and simulate the HA model.

1.2.2. Hybrid Bond Graph

Introduced by Paynter (1961), BG is a graphical representation of the continuous Dynamical Systems (DS). A BG model is constructed using different interconnected elements that represent the inner dynamic of the system. Each of these elements represents one basic fundamental phenomenon that exists in the nature. These fundamental elements are interconnected via power exchange bonds to construct a block model. Each bond is associated with two power variables: the effort e and the flow f. More formally:

Definition 1.1 (*BG*). A Bond Graph is a static oriented graph $BG(E, A_{BG}, J)$ where:

$E = \{S_e\} \cup \{S_f\} \cup \{R\} \cup \{I\} \cup \{C\} \cup \{TF\} \cup \{GY\} \cup \{D_e\} \cup \{D_f\}$ is the set of elements that represent the fundamental energetic processes. S_e and S_f are, respectively, the effort and the flow source elements. They supply energy which can be dissipated by the resistive R, or stored by the capacitive C and the inertia I elements.
TF and GY are TransFormer and GYrator used to represent energy conversion from one domain to another. D_e and D_f are effort and flow detectors associated with measurement functions.
A_{BG} is the set of the oriented bonds that represent the power exchange between the elements $el \in E \cup J$. They are associated with two conjugated variables: the effort e (above the bond) and the flow f (below the bond). The effort is the intensive variable (e.g. pressure, force, voltage) and the flow is the derivative of the extensive variable (e.g. volume flow, velocity, current). The power exchanges (energy variation) are determined through the so-called relation $P = e \times f$. The positive direction of the power flow is represented by the half-arrow on the bond (see Fig. 3).
J is the set of multiport-junctions used to connect elements of E by a 0-junction when the effort is the common variable and by a 1-junction when the flow variable is the same, an example is given in Fig. 3.