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Hybrid Dynamical System Monitoring based on Bond Graph

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***Abstract*— This paper considers the supervision of Hybrid Dynamical Systems (HDS) by bond graph (BG) approach. The bond graph is used for the detection and isolation faults affecting actuators, sensors or physical components of the process. The switching from one operated mode to another mode is described by an hybrid automata. The general principle of model-based FDI algorithms is to compare the expected behavior of the system, given by a model, with its actual behavior. The innovative interest of the present paper is the combined modelling Bond Graph and hybrid automaton for supervision of HDS. The proposed methodology is applied to a two tanks system.**

***Keywords*—hybrid dynamical system, bond graph, modeling, hybrid automata, supervision.**

I. INTRODUCTION

Many modern engineering systems are hybrid by nature. These systems contain both discrete and continuous components that interact together to create the global system trajectories [1]. Several classes of hybrid dynamical system models have been proposed in the literature [2] [3], each class is generally used to solve a particular problem. In this paper, hybrid automaton is the possible models that will be used because it is a successful modeling tool to analyze temporal behaviors.

As to the complexity of industrial systems, researchers are required to develop new approach applied to hybrid systems which is the Bond Graph (BG). Thereby, modelling is an important and difficult step because of the complexities of these systems and their control equipment, BG modelling is a unified multi-energy domain method, it provides an effective tool for dynamic modelling and for Fault Detection and Isolation (FDI) of hybrid systems [4].

Different approaches for the design of FDI procedures have been developed, depending on the kind of knowledge used to describe the plant operation. Two types of methods are used: qualitative and quantitative. In this paper, we are interested to the quantitative method.

Using quantitative approaches, called model-based methods, the first step generates a set of residuals called *analytical redundancy relations* (ARRs) and through elimination of unknown variables from the corresponding BG model using causal path, ARR equations can be obtained and Fault Signature (FS) can be established [5]. These fault indicators express the difference between information provided by the actual system and that delivered by its normal operation model. The residuals characterize the system operating modes that are close to zero in normal operation and different from zero in faulty situations. The number of residuals theoretically is equal to the number of sensor in the system.

In the present paper, we are interested in the BG modelling which is a unified multi-energy domain method provides an effective tool not only for dynamic modelling but also for Fault Detection and Isolation (FDI) of hybrid dynamic systems. In fact, our objective is to model a particular class of hybrid dynamical systems called switching systems with the hybrid automata and the bond graph approach.

This paper is organized as follows. Section II describes Hybrid Dynamic System model. The proposed modeling of Hybrid Automata which consist of modeled the continuous evolution of the system by bond graph model are developed in Section III. The general principle of residual-based FDI for the fault detection, isolation and the generation of ARRs are presented in section IV. A two-tank system is presented in section V to illustrate our approach. Finally, a conclusion is given in Section VI.

II. HDS MODELLING

In this section, we present the Hybrid Dynamical System modelled by the hybrid automata.

Definition 1: A hybrid automaton is a graph with places and directed arcs that represent the discrete transitions which connect the places. Any directed arc has a destination place. A hybrid automaton is formally described by the 8-tuple [6].

$$\left\langle Q, X, G, Inv, Act, Y, \sigma^s, \sigma^f \right\rangle$$

where

- $Q=\{q_i;\in M\}$ is the finite set of discrete states,
- $X=\{X_i;\in M\}$ is the set of continuous states, X_i denotes the acceptable state-subspace of mode *i*.

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$x_i(t) \in X_i(\dim x_i(t) = n_i)$ *is* the continuous state vector at time *t* in mode *i*.

- *G* represents the set of all inequality constraints,
- *Inv* represents the set of inequality constraints,
- *Act* represents the set of continuous activities,
- $Y = Y_c \cup Y_d$ is the set of measured outputs where Y_c is the set of continuous outputs, and Y_d the set of discrete outputs,
- σ^s, σ^f define respectively the spontaneous and forced transition (switching).

III. PROPOSED APPROACH

This section describes the proposed modeling combined the Hybrid Automata and the bond graph approach.

A. Bond Graph model

An industrial process has a highly complex behavior because of the mutual interaction of several phenomena that implement different kind of energy (mechanical, electrical, hydraulics, thermodynamics, chemical, etc...)[4]. So the bond graph is an excellent tool to model these systems. It has been defined by Henry Paynter 1961 [7], subsequently developed by Karnopp in 1975 [8] and Rosenberg in 1983[8][9].

The bond graph modeling is based on the exchange of power in a system, which in normally the product of an effort variable and a flow variable. This exchange takes places in bonds represented by a simple line [4].

The concept of power *p(t)* is described by the following equation:

$$p(t) = e(t).f(t) \tag{1}$$

Where *e(t)* and *f(t)* are the effort and the flow respectively. This equation illustrates the energy transfer in the system using power links. A link power is symbolized by a half-arrow, whose orientation indicates the direction of power transfer.

B. Bond Graph-Hybrid Automaton Coupling

The bond graph is a unified graphical language used for any kind of a physical domain. This tool is confirmed as a structured approach for modelling and simulation of multidisciplinary systems.

The hybrid automaton is a representation tool explicitly covering the continuous and discrete aspects of the SDH. The behavior of hybrid system is described by both continuous and discrete states that interact together to generate the inclusive system trajectories. These trajectories can be modeled by a sequence of continuous behaviors. The proposed approach consists to model the continuous evolution of the system by a bond graph. Each continuous behavior represents a state of the system. Discrete transitions from one mode to another one are defined by logic conditions C_1. The transition makes the switching from one state (mode) to another, if the condition defining the change is true (figure 1).

Hybrid system models have continuous dynamics described by standard differential state equations (possibly nonlinear), and discrete dynamics modeled by finite state machines. Our approach consists of modeling the continuous state by a bond graph model.

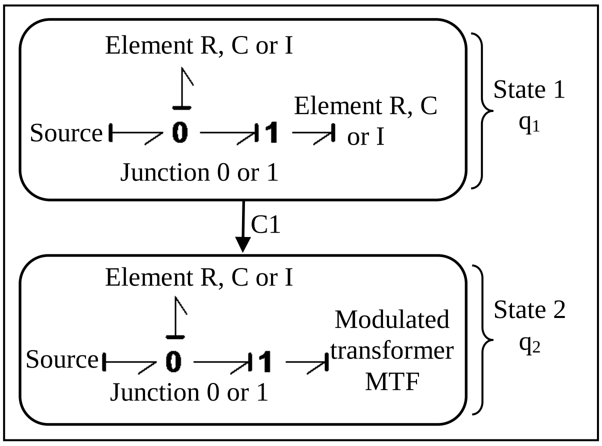

Fig. 1. Automata modelled by the BG approach

IV. SUPERVISION OF HDS

This part presents the generation of ARRs by BG for FDI system.

A. FDI by Bond Graph

The method for generating FDI algorithms by BG based on causal path is proposed by [10]. The goal is to explore all paths at the junction of sensors and sources. The methodology is then extended by [11][12] to design a supervision system, as shown in figure 2.

Generally, BG method is considered as not only a modeling tool, but also as a methodology for analysis of dynamical systems and also as an auxiliary technique for controller design [11]. Moreover, a BG model allows a structure analysis of the system and offers different techniques for model simplification, order reduction and sensor placement [4].

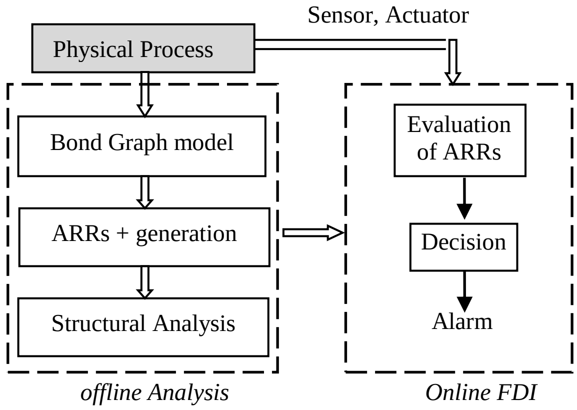

Fig. 2. Diagnosis system design

B. *Analytical Redundancy Relations*

The Analytical Redundancy Relations (ARRs) are relationship between the known variables[4][15]. Theses relations express the difference between information provided by the actual system and that delivred by its normal operation model. The number of redundancy relations derivable from any system model is equal to the number of sensors in the system.

The ARR is determined from the bond graph model in the system and takes the following form:

$$f(k) = \left(D_e, D_f, S_e, S_f, MS_e, MS_f\right) \qquad (2)$$

Where

- De, Df are effort and flow sensors,
- Se, Sf are effort and flow sources,
- MSe and MSf are modulated effort and flow sources,
- θ is represented a set of parameter,

Residual symbolized by r is the numerical value of ARR (evaluation of ARR) that can be written as follow:

$$r - f(k) = 0 \qquad (3)$$

Where k is the set of known variables (sources and measured values specified by detectors).

V. ILLUSTRATIVE EXAMPLE

In order to illustrate the effectiveness of the proposed approach, consider the hydraulic system [2] that is described in figure 3.

A. *System description*

This hybrid system is composed of:

- Two tanks T_1 and T_2 with the same section S are connected by pipes which can be controlled by different valves.
- A pump *P* that delivers a liquid to tank T_1.
- Three switching valves V_1, V_3 and V_4.
- Two level sensors: one level sensor that measures h_1 and the other level sensor measures h_2, the liquid level in tank T_2.

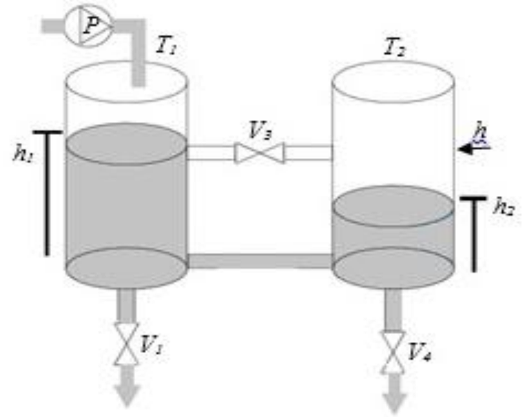

Fig. 3. Scheme of two-tank system

Theses valves can take the two states *Open (O)* or *closed (C)*. The pipe P_3 can take also the two states *full (F)* or *empty (E)*, when one of the levels h_1 or h_2 is higher (respectively lower) than *h*.

Thus, by considering the state of valves and the state of the pipe P_3, 2^4 operation modes can be considered.

The three valves V_1, V_3 and V_4 are controlled manually by the operator. We suppose that the system is used in a given *exploitation mode* in which V_1 and V_3 are always opened. So only valve V_4 is used. Supposed that V_4 is opened only if the level of the liquid in tank 1 is higher than *h.*

B. *Approach BG-Automaton*

Each mode is modeled by a bond graph model and the hybrid automaton that represents the hybrid system is given by figure 4.

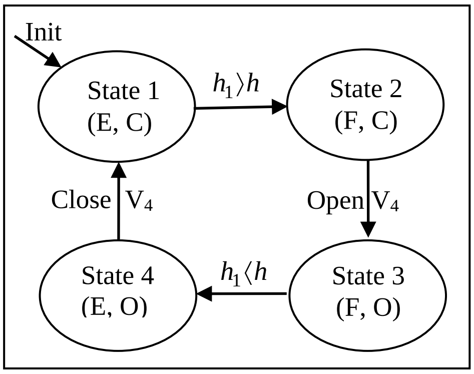

Fig. 4. Hybrid automaton of the hydraulic system

The physical quantities characterizing the hydraulic system are the flow and pressure which correspond to the flow and effort in terminology bond graph. Using the bond graph approach, the various elements of the system are modelled as follows (figure 5, 6, 7, 8).

- The pump is modelled by a flow source Sf,
- The tanks are modelled by storage-elements C,
- The various connections between components system are modelled by "0" junctions in the case of equal pressure and "1" junctions in the case of equal flow.

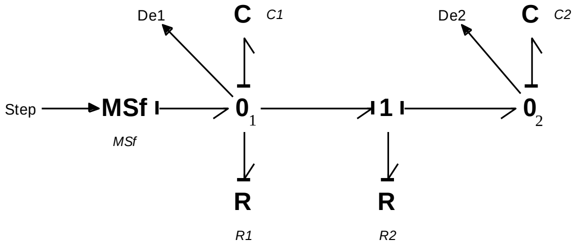

Fig. 5. Bond graph model of two-tank system (Mode 1)

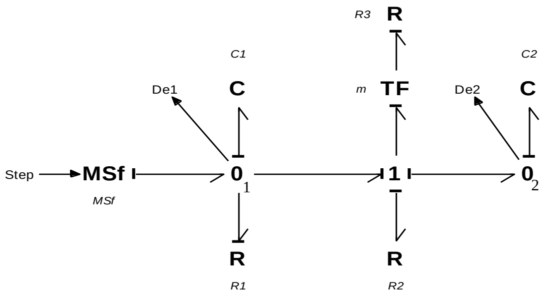

Fig. 6. Bond graph model of two-tank system (Mode 2)

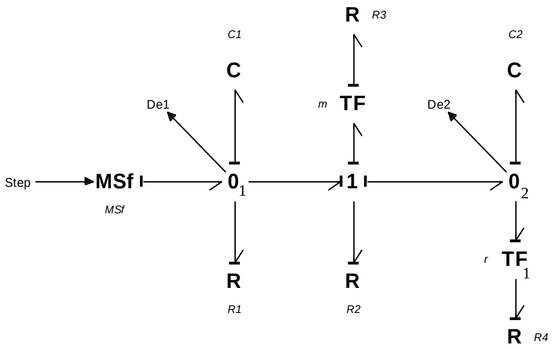

Fig. 7. Bond graph model (Mode 3)

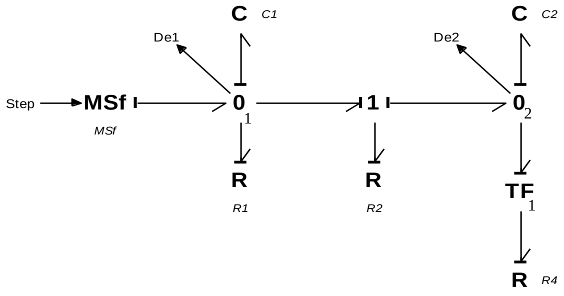

Fig. 8. Bond graph model (Mode 4)

The discrete evolution is given by figures 9 and 10. The switching between modes occurs every second. The system switches from one mode to another in a spontaneous way. The cycle is repeated several times.

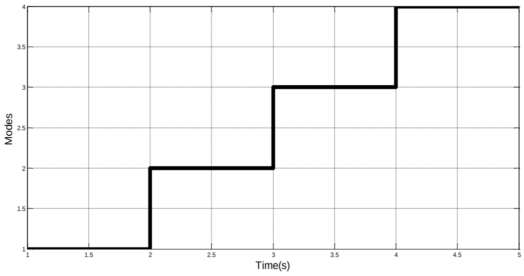

Fig. 9. Evolution of modes

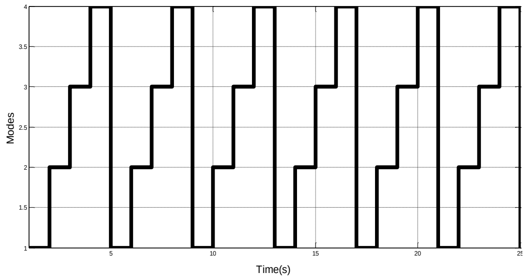

Fig. 10. Evolution of modes

C. *FDI by Bond Graph modelling*

In table I, it is given the structural equations deduced from Bond graph modelling of process corresponding of mode 3 (show figure 7). For each mode, we have generated the ARRs for FDI by bond graph model. We combined the equations presented in table I to eliminate unknown variables. The known variables are available from sensors and actuators, so we generate the set of residuals in which the appeared variables are all known.

TABLE I
STRUCTURAL EQUATIONS FOR NORMAL MODE

N	Junction	Structural equations
1	Junction 0_1	$\begin{cases} e_1 = e_2 = e_3 = e_4 = De_1 \\ Msf - f_{c1} - f_{R1} - f_4 = 0 \end{cases}$
2	Junction 1	$\begin{cases} f_4 = f_5 = f_7 = f_8 \\ e_4 - e_5 - e_7 - e_8 = 0 \end{cases}$
3	Junction 0_2	$\begin{cases} e_8 = e_9 = e_{10} = De_2 \\ f_8 - f_9 - f_{10} = 0 \end{cases}$

The first junction 0_1 equation as follows:

$$Msf - f_{c1} - f_{R1} - f_4 = 0 \qquad (4)$$

By replacing the flow *f* by its expression generated from the BG after eliminating the unknown variables, the residual 1 is obtained as follow:

$$r_1 = Msf - C_1\frac{dDe_1}{dt} - \frac{De_1}{R_1} - C_2\frac{dDe_2}{dt} + \frac{r^2 De_2}{R_4} = 0 \qquad (5)$$

The equation (5) shows that the residual r_l is sensitive to these elements (MSf, C_1, C_2, De_1, De_2, R_1 and R_4). Consequently, when fault is occurred in each elements described above, the residual r_l becomes different of zero.

The second junction O_2 gives us the following equation:

$$f_8 - f_9 - f_{10} = 0 \qquad (6)$$

According to these equations, we can deduce the residual equation r_2:

$$r_2 = C_2\left(R_2 + m^2 R_3\right)\frac{dDe_2}{dt} - \left[\left(\left(R_2 + m^2 R_3\right)\frac{r^2}{R_4} + 1\right)De_2\right] + De_1 = 0 \quad (7)$$

The equation (7) shows the residual is sensitive to these elements (C_2, De_2, De_1, R_2, R3 and R_4).

The faults signatures (FS) of different variables are grouped in table II.

TABLE II
FAULTS SIGNATURES (FS) FOR FDI

	r_1	r_2
Msf	1	0
De_1	1	1
De_2	1	1
C_1	1	0
C_2	1	1
R_1	1	0
R_2	0	1
R_3	0	1
R_4	1	1

D. *Simulation Results*

The simulation have been performed by the software Matlab and 20 sim. The normal evolutions of residuals are presented in figure 11. Simulation time is fixed to 10s. There are disturbances in the residuals which lead us to choose a detection threshold ±1.

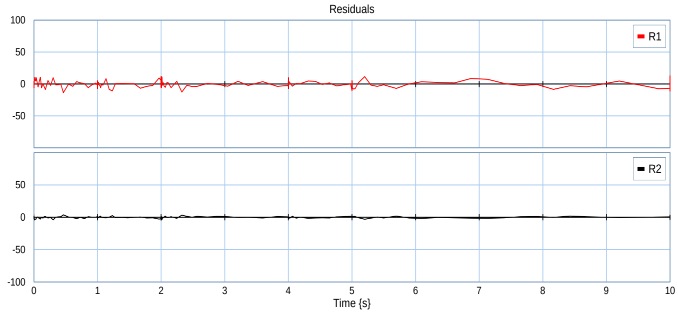

Fig. 11. Residuals in normal operation

A fault is simulated at the pump (modelled by MSf in BG) in the interval time [4s, 5s]. Figure 12 shows that r_1 is sensitive to the introduced fault. This is confirmed by the FS presented in table II.

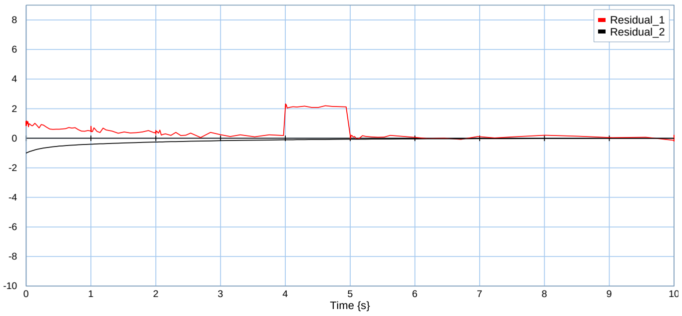

Fig. 12. Residuals in failure mode (Pump failure)

When the system operates in mode 4, multiple faults have been introduced at the actuator (pump) in the interval time [2s, 3s] and at the sensor De_2 between the instant t=6s and t=8s. Figure 13 shows that the residual r_1 is sensitive to these faults. This is confirmed by the FS presented in table II.

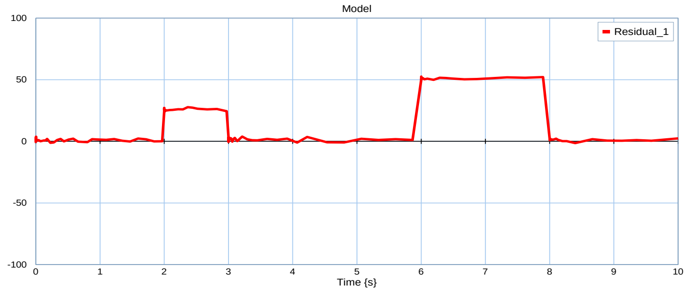

Fig. 13. Residuals in failure mode (Pump and Sensor failures)

VI. CONCLUSION

In this paper, it is shown that the bond graph as a dynamic and efficient modelling tool (because of its graphical, structural and causal properties) and its methodology can be used not only for dynamic modelling but also for Fault Detection and Isolation (FDI). A particular class of hybrid dynamic systems called switching systems is modelled using the hybrid automata and the bond graph approach. The ARRs are generated directly from a bond graph model. The use of a bond graph as an integrated design tool for modeling and monitoring of a hybrid system is well justified by the simulation results of an hydraulic hybrid system.

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