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# DIAGNOSIS APPROACH USING BOND GRAPH AND TIMED AUTOMATA

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**ABSTRACT:** The problem of fault diagnosis involves detecting, locating and identifying the considered faults occurring in the dynamical system. The aim of this paper is to explain the use of hybrid tool which combines Bond Graph (BG) and Timed Automata (TA). These tools allow us, respectively, to detect the fault and find the cause of a system dysfunction. Due to the structural and causal properties of the bond graph tool, we use it to detect the incorrect behavior and then to isolate faults which can affect the physical process. But sometimes, some failures of the system components can not be identified by the Bond Graph model. Therefore, we use, in this case, the timed model (timed automata) in order to locate and identify these faults. And subsequently, the performances of the phase of fault location will be improved (i.e. isolation of non-isolable faults) thanks to the use of these tools (Bond Graph and Timed Automata). The proposed approach is then validated through simulation tests to a level regulation system.

**KEYWORDS:** Diagnosis, Bond Graph, Timed Automata, fault location.

## 1 INTRODUCTION

The main purposes of this paper concern residual generation and fault isolation based on a new approach which combined the causal graphical approaches (Bond graph and causal graph) and the timed automata. The bond graph model is used to generate systematically a set of fault indicators called also analytical redundancy relations (ARRs) deals with the FDI (Gertler, 1998; Patton *et al.*, 2000; Staroswiecki and Comtet-Verga, 2000). This modeling approach provides an effective tool for compositional modeling, by their representation and by phenomena of storage, dissipation and transformation of energy thanks to the bond graph elements (R, C, I, TF, GY, ...), and also for fault detection and isolation (FDI) of dynamic systems (Cellier, 1991; Dean *et al.*, 2000). ARR are designed; the fault detection procedure checks the presence of fault indicated by a non-zero value of these indicators. The localization procedure by bond graph is based on the fault signature matrix generated from the ARR. But this phase of location, generally, is not more effective thanks to not isolable of some defect. To improve performance of fault isolation, we use the timed automata. In the approach we propose here, the diagnosis system is based on checking the consistency between the time of failure occurrences and the inputs sequences. It is thus necessary to know the time trajectories. A dynamic model with temporal transitions, in our approach, is proposed for which the defective states are identified. The goal is to find the coherent diagnostic way, which corresponds to the defective evolution of the system. The verification of this model is based on the backward exploitation of the dynamic model, where all

possible reverse paths are searched. The reverse path is the connection of the faulty state to the initial state.

This paper is organized as follows: In the next section, a proposed procedure for FDI is described. Section 3 and 4 give, respectively, an idea quantitative on bond graph (BG) and timed automata (TA) approaches, by using to develop diagnosis approach. In Section 5, an academical example is used to illustrate our approach. Finally, a conclusion is presented with some perspectives.

## 2 PROPOSED DIAGNOSIS APPROACH

The proposed FDI approach combines two tools: the bond graph and timed automata is shown in figure 1, where variables  $u$  and  $R$  are respectively input state and the set of residuals.

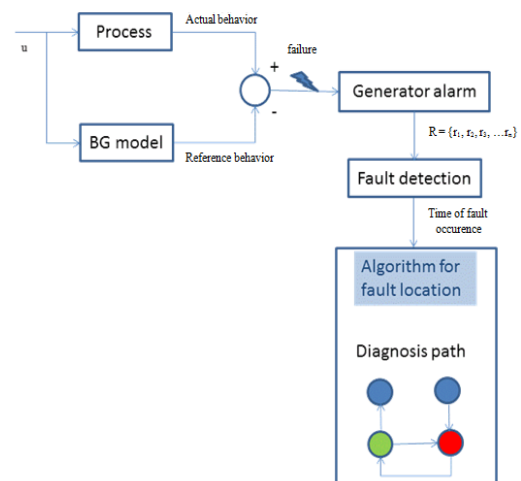


Figure 1: Principle of the fault location

The quantitative approach is based on the bond graph model which allows the generation of the fault indicators and on the dynamic model (TA) which presents a tool of fault location and isolation. The exploitation of the data resulting from the comparison of the current functioning system with its bond graph model (figure 1) allows to generate a set of indicators of faults (residuals), which allows, thereafter, to detect any possible malfunctions and to locate the source of a fault from the fault signature matrix. But once where the fault is not identified by the bond graph model, the diagnostic technique for fault location is then based on time analysis by using the timed automata model, where the coherent trace is searched by the verification of elapsed time with global time of alarm. We consider a plant equipped with an alarm and with a global clock for synchronization. Alarm produces an error signal when a fault is detected. Our diagnosis task is to locate and identify all faults which can occur (figure 1). The aim is to find the coherent diagnostic path, which corresponds to the faulty evolution of the system. In our case verification (analysis) means searching accessible trace of timed automata (reverse path). This reverse path project the evolution of the system, from a final faulty state to the initial state (Simeu, 2010). The reverse path is also called diagnostic path. We suppose the initial state is known. Our task can be seen as retrace the automaton graph from the faulty states to the known origin state. The aim is to find from the set of reverse path the coherent ones.

### 3 BOND GRAPH ANALYSIS

Bond graphs are a domain-independent graphical description of dynamic behavior of different physical systems (mechanical, electrical, hydraulic ...). The basis is that bond graphs are based on energy and energy exchange. From the structural and causal properties, the bond graph tool allows to highlight the effects and the causes, allowing, thereafter, to find the origins of alarms. BG modelling is a powerful tool for modelling engineering systems, especially when different physical domains are involved.

The concept of bond graphs was originated by (H. M and Paynter, 1961). The idea was further developed by Karnopp and Rosenberg (Karnopp and Rosenberg, 1974), such that it could be used in practice (Jean, 1989; Breedveld, 1986). A number of methods have been developed for fault detection and isolation. All methods of fault detection work by designing residual functions. The residual represents the difference between an estimated value and a measured one, which should be zero during normal operation (without fault), but large in the presence of faults (Cellier, 1991). This residual is generated from analytical redundancy relations (ARR). The ARRs are generated in the form of symbolic relations from a bond graph model in derivative causality. In the case where the complex bond graph model presents implicit relations, complex non-

linearities, the ARRs must be to generate numerically after the modifications considered necessary on the bond graph model in derivative causality. After these modifications (Samantaray et al., 2006), the diagnostics bond graph (DBG) model is obtained in which the inputs are values of sources and sensor measurements and the outputs are numerical values given by the detectors of numerical residuals. According to these modifications, each sensor is corresponds a numerical detector residual. Therefore, the number of residual generated is equal to the number of sensors present in the system.

### 4 TIMED AUTOMATA

The timed automata tool (Sava, 2001; Simeu et al., 2003) is defined as a finite state machine with a set of continuous variables that are named clock. These variables evolve continuously in each location of the automata, according to an associated evolution function. As long as the system is in one state  $L_i$ , the clock  $x_i$  is continuously incremented. Its evolution is described by  $\dot{X}=1$ . The clocks are synchronized and change with the same step. An invariant is associated to each state. It corresponds to the conditions needed to remain in the state. The number of clocks depends on the parallelism in the system. The automata can stay in one state as long as the invariant condition is checked. Each transition of an automata is conditioned by an event or temporization called “guard” and its execution determines the discrete evolution of the variables according to its associated assignment.

Let us consider the timed automata given in figure 2. This automata has two clocks  $x$  and  $y$ . The continuous evolution of time in this model is represented by  $\dot{x}=1$  and the labeled arcs in the graph represent the model of discrete evolution. The guard in each arc is a transition labelling function that assigns firing conditions with the transitions of the automata. The affectation is a function that associates with each transition of the automata one relation that allows actualizing the value of continuous state space variables after the firing of a transition. The invariant in the state  $S_0$  and  $S_1$  are respectively  $y \leq 5$  and  $x \leq 8$ . The initial state of this system is represented by an input arc in the origin state ( $S_0$ ). In the dynamic model, active clocks are found in each state. A graphical interpretation of the timed automata is the automata graph (figure 2).

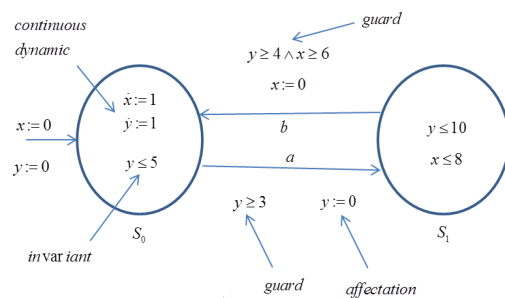


Figure 2: Example of Timed Automata

In our case verification (analysis) means searching accessible trace of timed automata (reverse path). This reverse path project the evolution of the system, from a final faulty state to the initial state. We suppose the initial state is known. Our task can be seen as retrace the automaton graph from the faulty states to the known origin state. The aim is to find from the set of reverse path the coherent ones. The principle of the analysis is shown in automaton graph with fault model (figure 3). From fault model one can see that fault F1 can occurs from states 2, and the fault F2 from the state 3. The diagnostic model must be defined that if fault occurs in the system, fault must be located according the time instant t. If the fault occurs in the time t=4, it's fault located as F1. In another case, the fault occurs in the time t=6, the fault F2 is located.

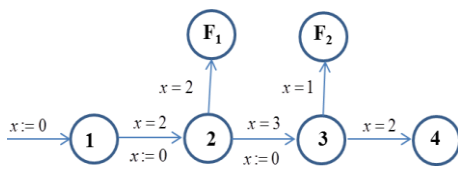


Figure 3: Principle of the backward time analysis

## 5 APPLICATION EXEMPLE

### 5.1 Description of the system

This unit (figure 4) consists on a hydraulic circuit, with a bottom tank (1) and a superior process tank (2), both dual ones, two pumps of centrifugal circulation (3), two flowmeters with a manual control valve (4), three on/off solenoid valves (5) and a motorized proportional valve (infinitely variable) (6). Of course, together with the tubes, the union elbows, connections, feedthrough, main valve and the appropriate drainage for the circuit operation.

As additional fixed elements, there is also a turbine flow sensor that is installed in one of the upward lines of flow (8), and a temperature sensor located in a lateral bottom of the process tank (9) together with a serpentine with electric heating (11). The interchangeable additional elements are an agitator (10), the immersion level sensor should be located in the process tank (12) and the pH sensor (solenoid), can be in the process tank or also in the second tank (13), to study the effect of the time out.

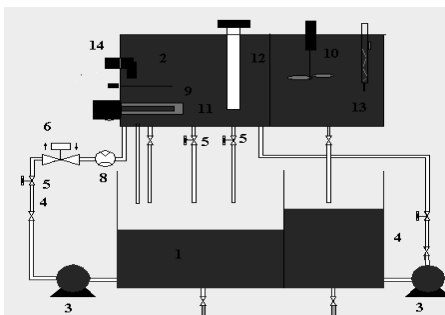


Figure 4: Main diagram of the equipment

### 5.2 Operation of the subsystem

For the level, flow and temperature control test, the liquid (water) is impelled from the tank by the pump, located to the left of the front of the equipment, going through the flowmeter, the solenoid valve (usually open), the motorized valve, the turbine (flow sensor) and the process tank. It is possible to use the second pump in the level tests, as it will be indicated. The process tank is divided in two halves, with an orifice between them that allows their communication or isolation. The right compartment has an overflow of variable level (that it prevents the complete overflow of the tank, and it allows to modify its effective liquid volume), two drains with solenoid valves with different Cv (normally closed), and a third one with a normal drainage valve. The left compartment is only connected to a drainage valve. The level control tests require all the elements of the circuit and of the tank, besides the sensor located in it. In some experiments, it is required the second pump placed to the right-hand side of the equipment. The water is heated by an electric resistance AR-1(11). The action of heating is conditioned by the order of All or Nothing level sensor AN-1(14).

We include in the following table 1 the constituent elements of the equipment and a brief description of each.

Identification	Description
ST-1	Upper tank Temperature Sensor
SC-1	Flowmeter
SpH-1	Ph meter
SN-1	Upper tank Water level sensor
AN-1	Upper Tank Water Level Switch
SP-1	Upper Tank Pressure sensor
AVS-1	Upper tank Inlet solenoid valve
AVS-2	Quick outlet Solenoid Valve of the upper tank
AVS-3	Slow outlet Solenoid Valve of the upper tank
AVP-1	Proportional Valve at the upper tank
AA-1	Upper tank stirrer
AR-1	Electric Resistance
AB-1	Recirculation Left Pump (Slow)
AB-2	Recirculation Right Pump (Quick)
VR-1	Manual valve flow meter (Left)
VR-2	Manual valve flow meter (Right)

Table 1: Description of the constituent elements of the system

### 5.3 Fault detection based on bond graph

For this unit, we applied, with the bond graph model, the main steps of the Fault Detection and Isolation. The detection procedure is based on the generation of fault indicators from the diagnosis bond graph (DBG) model by following the causal paths. The diagnosis bond graph

(DBG) model of the system obtained from the word bond graph model (figure 5) is given in figure 6.

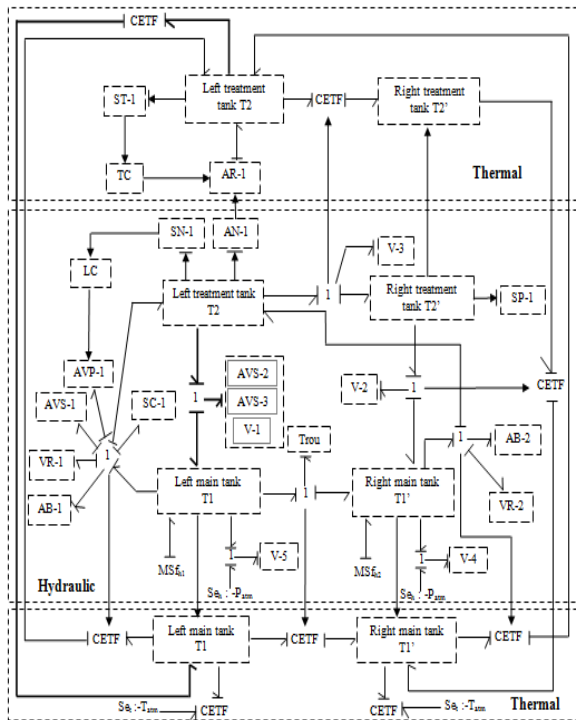


Figure 5: Word Bond Graph Model of System

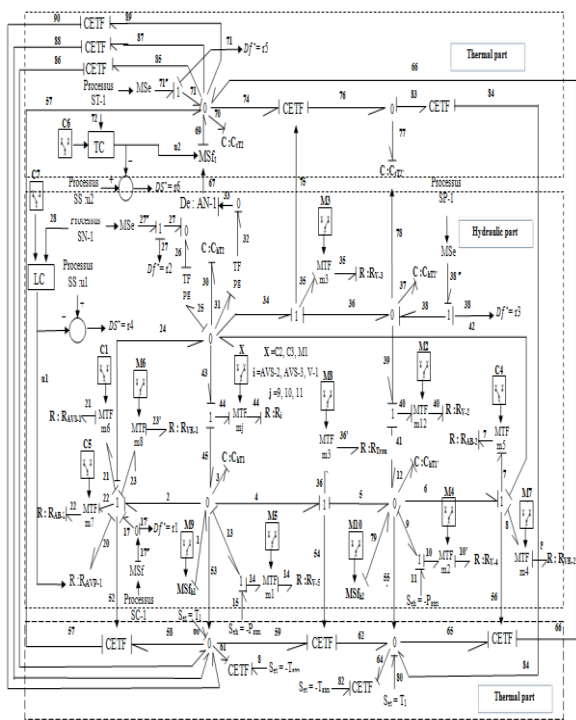


Figure 6: Diagnosis Bond Graph Model of System

The bond graph representation of the coupling of the two hydraulic and thermal phenomena is an open research domain. Certain authors represent the coupling by a multiport element  $R$  (Jean and Ould Bouamama, 2000).

In this paper, the  $CETF$  element indicated in the diagnosis bond graph (DBG) model in figure 6 represents the coupling element of the two hydraulic and thermal phenomena. The causal form of the  $CETF$  coupling element for thermo-fluid is given in figure 7.

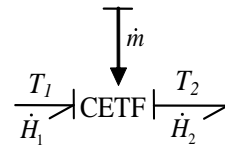


Figure 7: Representation of the CETF coupling element for thermo-fluid

Thus, the representation of energy storage in the bond graph model is represented by the  $C$  element. Therefore, the  $C_h$  and  $C_t$  elements shown in the diagnosis bond graph (DBG) model in figure 6 respectively represent, hydraulic energy storage and thermal energy storage. In the diagnosis bond graph model (figure 6), the effort sensor,  $\tilde{D}_e: SP-1$ , in inverted causality is considered as a source of effort modulated by the measured value which corresponds to a numerical residual represented by the  $Df^*: r3$  element. The modifications made to this type of detector are shown in figure 8.

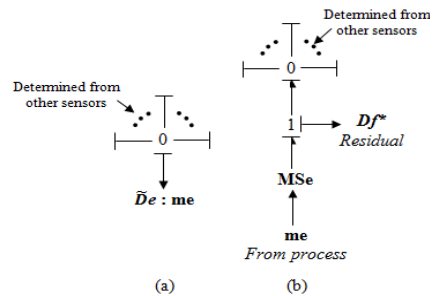


Figure 8: (a) Effort sensor,  $\tilde{D}_e$ , in inverted causality, (b) corresponding substitution and residual detector obtained

The same reasoning applies to effort sensors  $\tilde{D}_e: SN-1$  and  $\tilde{D}_e: ST-1$ . For the flow sensor,  $D_f: SC-1$ , whose causality is not inverted, the modifications proposed are given by the figure 9.

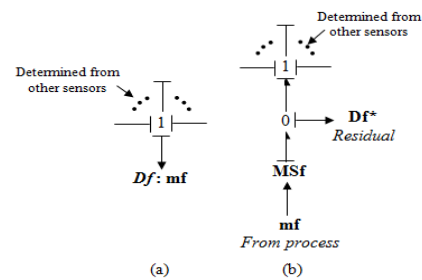


Figure 9: (a) Flow sensor,  $D_f$ , in non-inverted causality, (b) corresponding substitution and residual detector obtained



The DBG, in figure 6, has six access points (corresponding to the six sensors of the system) and six outputs (corresponding to the six numerical residuals) as shown in the block diagram in figure 10.

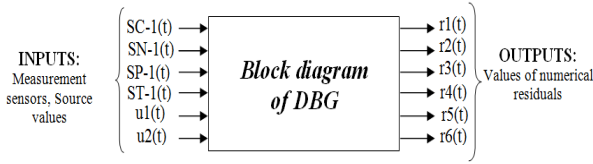


Figure 10: Block diagram of DBG

### 5.4 ARRs generation

Methods to derive ARRs from bond graph models by applying the causality inversion algorithm, have been presented in (Breedveld, 1986; Ould Bouamama *et al.*, 2003), which use structural and causal properties. In our case the diagnosis bond graph (DBG) model allows to obtain the values of numerical residuals and also the fault signature matrix  $S_{ij}$ . In fact, the latter is essential for the localization of defects that can arise during the system operation. The analysis of the causal paths of the unknown greatness towards the detector is used to generate the fault signature matrix (Table 2). Thus, a residual  $r_i$  is sensitive to a failure in the component  $Comp_j$  if and only if the variable of this component is found in the causal path allowing the generation of the residual  $r_i$ .

For example, the variables of components intervening in the detector of residual  $r_1$ , which is represented in the bond number 17' in figure 6, are determined by the following causal paths:

1.  $SC-1(t) \rightarrow f_{17'} \rightarrow f_{17'}$   
 $\rightarrow f_{23} \rightarrow R_{VR-1} \rightarrow e_{23} \rightarrow e_{22} \rightarrow R_{AB-1} \rightarrow f_{22} \rightarrow f_{17} \rightarrow f_{17'}$   
 $\rightarrow f_{21} \rightarrow R_{AVS-1} \rightarrow e_{21} \rightarrow e_{22} \rightarrow R_{AB-1} \rightarrow f_{22} \rightarrow f_{17} \rightarrow f_{17'}$   
 $\rightarrow f_{24} \rightarrow f_{42} \rightarrow f_8 \rightarrow R_{VR-2} \rightarrow e_8 \rightarrow e_7 \rightarrow R_{AB-2} \rightarrow f_7 \rightarrow f_{42} \rightarrow f_{17}$
2.  $SN-1(t) \rightarrow LC \rightarrow R_{AVP-1} \rightarrow e_{20} \rightarrow e_{22} \rightarrow R_{AB-1} \rightarrow f_{22} \rightarrow f_{17} \rightarrow f_{17'}$
3.  $SN-1(t) \rightarrow e_{27} \rightarrow e_{27} \rightarrow e_{26} \rightarrow TF \rightarrow e_{25} \rightarrow e_{24} \rightarrow e_2 \rightarrow e_3 \rightarrow C_{kT1} \rightarrow f_3 \rightarrow f_2 \rightarrow f_{17} \rightarrow f_{17'}$   
 $\rightarrow e_{42} \rightarrow e_7 \rightarrow R_{AB-2} \rightarrow f_7 \rightarrow f_{42} \rightarrow f_{24} \rightarrow f_{17} \rightarrow f_{17'}$   
 $\rightarrow e_6 \rightarrow e_{12} \rightarrow C_{kT1} \rightarrow f_{12} \rightarrow f_6 \rightarrow f_{42} \rightarrow f_{24} \rightarrow f_{17} \rightarrow f_{17'}$

The components involved in the residual  $r_1$ , from these causal paths, are thus given by the vector  $KI = [SC-1, RVR-1, RAVS-1, RVR-2, RAB-1, RAB-2, SN-1, LC, RAVP-1, tank T1, tank T1']$ . This signature can be written in the terms of components  $KI = [SC-1, Valve VR-1, Valve AVS-1, Valve VR-2, Pump AB-1, Pump AB-2, SN-1, LC, Valve AVP-1, tank T1, tank T1']$ . Thus, the application of this procedure on all numerical detectors of residuals leads to the fault signature matrix  $S_{ij}$ . The

failure signature matrix, for all the devices (components, sensors, and controllers) of the level regulation system example, in figure 4, is given in Table 2.

Components	r1	r2	r3	r4	r5	r6	$D_b$	$I_b$
<b>u1</b>	0	0	0	1	0	0	1	1
<b>u2</b>	0	0	0	0	0	1	1	1
<b>Df :SC-1</b>	1	0	0	0	1	0	1	1
<b>De :SN-1</b>	1	1	1	1	1	0	1	1
<b>De :AN-1</b>	0	0	0	0	1	0	1	0
<b>De :SP-1</b>	0	1	1	0	1	0	1	1
<b>De :ST-1</b>	0	0	0	0	1	1	1	0
<b>Left main tank T1</b>	1	1	0	0	0	0	1	0
<b>Right main tank T1'</b>	1	1	0	0	0	0	1	0
<b>Left treatment tank T2</b>	0	1	0	0	1	0	1	1
<b>Right treatment tank T2'</b>	0	0	1	0	0	0	1	1
<b>Pump AB-1</b>	1	1	0	0	1	0	1	1
<b>Pump AB-2</b>	1	1	0	0	0	0	1	0
<b>Valve VR-1</b>	1	1	0	0	0	0	1	0
<b>Valve VR-2</b>	1	1	0	0	0	0	1	0
<b>Valve AVS-1</b>	1	1	0	0	0	0	1	0
<b>Valve AVP-1</b>	1	1	0	0	0	0	1	0
<b>Valve V-3</b>	0	1	1	0	0	0	1	1
<b>Electric Resistance AR-1</b>	0	0	0	0	1	0	1	0
<b>Level controller LC</b>	1	1	0	1	1	0	1	1
<b>Temperature controller TC</b>	0	0	0	0	1	1	1	0

Table 2: Fault signature matrix

It is important to underline that this fault signature matrix built by following the causal paths corresponds to a well determined configuration and therefore to an associated model. The form of the equations for each bond graph element is then the same during the whole period of functioning in a given configuration. For example, the total blocking of the valve AVS-1 represented by the element RAVS-1 causes the rupture

of all the causal paths of (and towards) this element. By analyzing this matrix, we see well that the variable associated with each component is present in at least one residual. So all system failures are theoretically detectable ( $\mathbf{D}_b = \mathbf{1}$ ).

Moreover, the signatures of components SN-1, SC-1, u1, u2, SP-1, AB-1, V-3, tank T2, tank T2 'and LC are unique. Thus, the failures of these components are isolatable ( $\mathbf{I}_b = \mathbf{1}$ ).

On the other hand, the signatures of components AN-1 and AR-1 are identical what means that the failures affecting these components cannot be isolated ( $\mathbf{I}_b = \mathbf{0}$ ).

*Our contribution in this paper is the use of timed automata for the isolation of these non-isolable components by Bond Graph model.*

### 5.5 Fault isolation base on timed automata

The timed automaton model of the level regulation system of figure 4 will become bulky and complicated by its significant number of fault state. And the visualization of this model will become, thereafter, incomprehensible. For this reason and for the phase of localization of faults (valve fault AVP-1, sensor fault AN-1, valve fault AVS-2) we consider only part of the model shown in figure 11. The goal being the study of level in a tank by the action on valve AVP1 and also by two sensors SN1 and AN1, respectively, of high and low level measurement. The valve AVS2 allows to drain the tank.

We use the timed automaton model for isolate faults in the components (AVP-1, AN-1, AVS-2) which are not identifiable (see table 2).

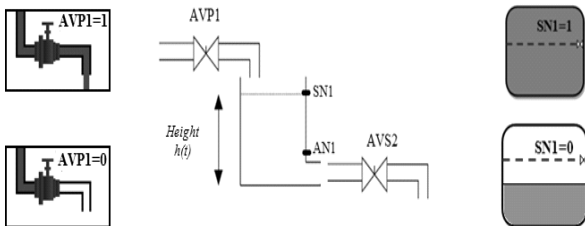


Figure 11: Schema of tank system

In the initial state, the tank is empty. At the moment when contact "On" closes, the tank is filled by the product thanks to the opening of valve AVP1. When the tank level SN1 is reached, the valve AVP1 is closed and AVS2 is opened up to the level is below AN1.

#### Control sequence

- (1) S0: The tank is empty. Sensors AN1 and SN1 are in the state 0.
- (2) S1: The "On" button is activated. Valve AVP1 is open, a liquid flows into tank up to level SN1.
- (3) S2: If level SN1 is reached then valve AVP1 is closed and AVS2 is opened, the tank is emptied up to the empty level (AN1=0). Then the cycle starts again.

The phase of fault location consists in finding how to isolate a fault, in other words how the fault going to propagate in the system. This phase is based on time analysis where the coherent path is searched by the checking between input sequences and the moment of failure events. Therefore, it is necessary to know the time trajectories.

In our case, we consider eight faults and their failure modes which are summarized in table 3.

N°	Failure mode	Réf
1	Does not detect the rising level	AN1_SO
2	Does not detect the lower level	AN1_SC
3	Does not detect the rising level	SN1_SO
4	Does not detect the lower level	SN1_SC
5	Remains closed during an opening request	AVP1_SC
6	Remains open during a closing request	AVP1_SO
7	Remains closed during an opening request	AVS2_SC
8	Remains open during a closing request	AVS2_SO

Table 3: Faults and their failure modes

Before passing at the step of fault location, a means of detection, for each fault listed in table 3, is set up (see table 4).

faults	Detection parameters	State
AN1 Stuck_Open	From the opening of the drainage valve AVS2, sensor AN1 should not pass to state 0 before 321.9 sec.	S3
AN1 Stuck_Close	Sensor AN1 will have to pass to state 0; 321.9 sec after the opening of the drainage valve.	S4
SN1 Stuck_Open	Sensor SN1 must pass to state 1; 97.9 sec after the opening of the valve AVP1.	S0
AVP1 Stuck_Close		
SN1 Stuck_Close	Sensor SN1 must pass to state 0 directly after the activation of the valve AVS2.	S2
AVP1 Stuck_Open		
AVS2 Stuck_Close		
AVS2 Stuck_Open	Sensor SN1 must pass to state 1; 60 sec after the opening of the valve AVS2.	S1

Table 4: Detection parameters of the process

For the eight faults listed in table 3, we use only five states of detection (S0, S1 ... S4). The table 5 below shows us the necessary conditions to localize the defects.

State	Localization parameters	faults
S0	The AN1 sensor, passes to state 0; 11.9 sec after activation of the S0 detection.	SN1 Stuck_Open
	The AN1 sensor, remains in state 0; 20 sec after activation state S0 detection.	AVP1 Stuck_Close
S1	the detection suffices to the localization	AVS2 Stuck_Close
S2	The AN1 sensor, passes to state 0; 100 sec after the activation of the state S2 detection.	SN1 Stuck_Close
	The AN1 sensor, passes to state 1; 100 sec after activation state S2 detection.	AVS2 Stuck_Close
	the detection suffices to the localization	AVP1 Stuck_Open
S3	the detection suffices to the localization	AN1 Stuck_Open
S4	the detection suffices to the localization	AN1 Stuck_Close

Table 5: Localization parameters of the process

The global automata graph which contains the faultless functioning states and all the faulty states for diagnosis of the level regulation system is shown in figure 12.

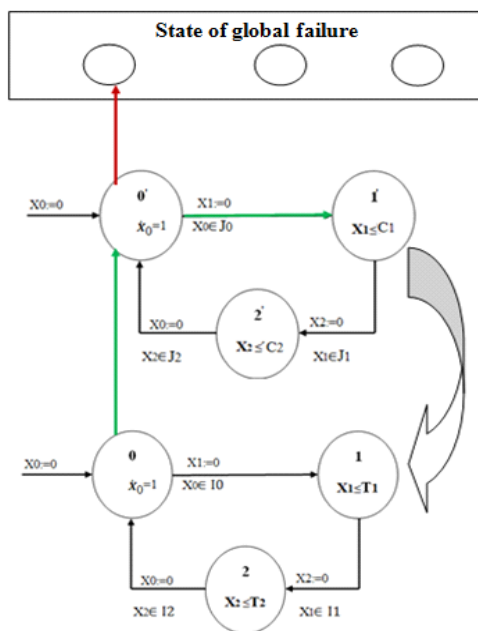


Figure 12: Diagnosis Automata Model of System

If the model of the whole system is built, the reading of the evolution of the system becomes very difficult. The

use of the timed automaton tool has only one drawback it is the explosion in the number of transitions between states in the three modes of operation. This problem of explosion in number of arcs is resolved by the use of the state flow tool (see figure 13).

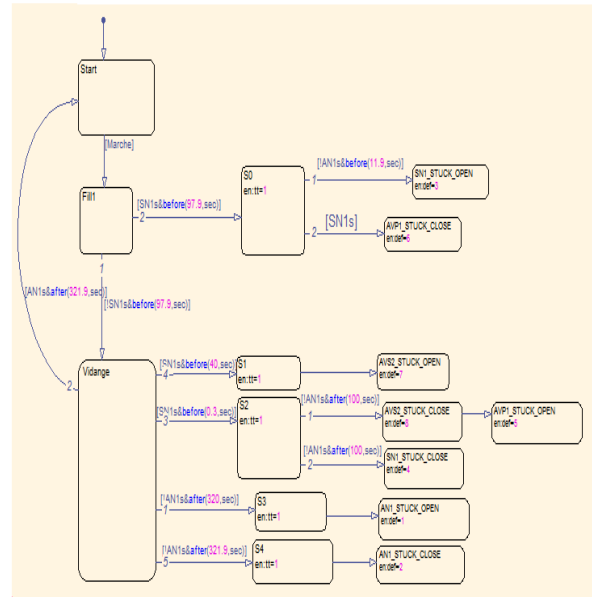


Figure 13: Isolation Model of System

The next step in our diagnosis is verification of this model by analyzing time back. It means to verify if all failed states in the dynamic model (TA) are reachable. When the time of occurrence of the defect is considered, the backward time analysis searches the possible reverse path to localize the failure according to the time of fault occurrence.

In our case exploitation means searching accessible trace according to the time from a final faulty state to the initial state of automaton denoted by reverse path. Therefore the initial state must be known. Our task can be seen as retrace the automaton graph from the faulty states to the known origin state. The aim is to find from the set of reverse path the coherent ones.

This algorithm based on the backward time analysis allows as from the moment of appearance of alarm, to localize the defect.

**Step 1:** Calculate the duration of an operating cycle (in our case, it is 418.9 sec).

**Step 2:** Calculate the number of cycles made by the process before the activation of the alarm.

$$\text{Number of cycles} = \text{round}(\text{Talarm}/418.9)$$

**Step 3:** Calculate the weight of the path:

$$\text{Path} = \text{Talarm} - (418.9 * (\text{number of cycle}))$$

**Step 4:** Compare the path value obtained with the weight of the different paths.

On the table below are listed the weights of different paths.



Fault	Time of path in sec
AN1 Stuck_Open	91
AN1 Stuck_Close	11
SN1 Stuck_Open	200
SN1 Stuck_Close	208.2
AVP1 Stuck_Open	209.1
AVP1 Stuck_Close	130.2
AVS2 Stuck_Open	12.2
AVS2 Stuck_Close	208

Table 6: Weights of different paths

## 6 SIMULATION RESULT

To illustrate the effectiveness of the diagnosis approach, we present simulation results of the level regulation system example. The bond graph and timed automata models of the system was constructed using MATLAB SIMULINK and state flow. Block diagram model of the Bond graph and block program are developed by the authors which are not presented in this paper.

Two failure scenarios have been simulated. The first concerns a failure of the flow sensor SC-1 during a time interval ranging from 3 to 15 s. Figure 14 shows the response of the residuals  $r_1$  and  $r_5$  and their sensitivity to this failure. If we refer to the signature of the component SC-1 (flow sensor) given in the table 2 we note that this result is well consistent with what is expected; in other words, in case of failure of the component SC-1 (flow sensor) only the residuals  $r_1$  and  $r_5$  will exceed their respective threshold.

*We will therefore be able to find this fault by the bond graph model.*

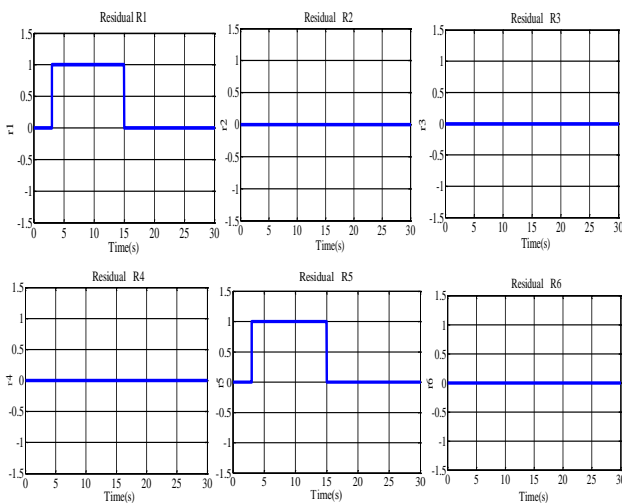


Figure 14: Response of the residuals following a failure at flow sensor SC-1

In the second failure scenario, the valve AVP1 has been blocked. Figure 15 allows us to compare a normal operation (left part) of the process with a state of faulty

operation (right part). On the right figure, despite the request of opening of the valve AVP1, it remains closed. This moment represents the occurrence of a failure.  $T_{occurrence} = 430.2$  sec. Then, the sensor SN1, remains in state 0; 97.9 sec after the request for the opening of the valve AVP1. This moment represents the moment of detection of the fault.  $T_{detection} = 528.1$  sec. S0 state (see figure 13).

Finally the sensor AN1, remains in state 0; 20 sec after the activation of the detection state. This time corresponds to the fault location.  $T_{localization} = 548.1$  sec. AVP1\_SC state (see figure 13).

This figure analysis shows that:

- Detection time =  $T_{detection} - T_{occurrence} = 97.9$  sec.
- Localization time =  $T_{localization} - T_{detection} = 20$  sec.

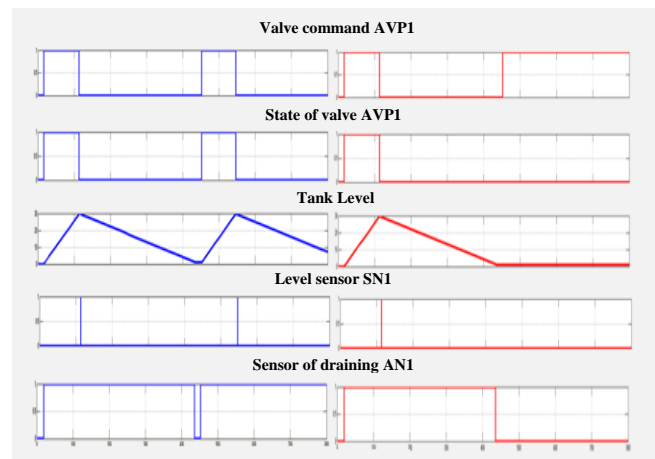


Figure 15: Diagnostic for the fault AVP1 Stuck- Close

### Verification by the backward time analysis

An alarm appears to  $T_{alarm} = 548.1$  sec (the time of appearance of alarm is the time of fault location,  $T_{alarm} = T_{localization} = 548.1$  sec)

According to the verification algorithm by the backward time analysis we have:

- 1 - The duration of an operating cycle is 418.9 sec.
- 2 - Number of cycles =  $\text{round}(548.1 / 418.9) = 1$
- 3 - Path =  $548.1 - (418.9 * 1) = 129.2$  sec

Therefore, from the table of the path (table 6), we can conclude that the valve AVP1 remains closed during an opening request (AVP1 Stuck\_Close).

*We will therefore be able to find this fault by the timed automata model because this fault cannot be located by the bond graph model.*

## 7 CONCLUSION

In this paper, a method for fault detection and isolation is presented. It is combining graphical approaches (BG) and the model of dynamical system (timed automata). Bond graph is used for detecting systematically actuators, sensor and structural fault. By following the procedure of generation numerical residuals from the DBG model, the construction signatures of the different com-

ponents of the system is then used to detect the various probable failures in system components. The procedure of fault location by the timed automata tool is used when the fault cannot be identified by the bond graph model. This approach is based on the trajectory and the temporal transition of the model which must be identified for all modes considered (faultless and faulty mode). And in order to improve the performance of the phase fault location by timed automata, the verification by the backward time analysis is presented. This verification is based on the backward exploitation of the dynamic model (TA), where according to the time of fault occurrence, all possible reverse paths of the faulty state to the initial state are searched.

The next step is interested in the event of fault diagnosis in the presence of common causes.

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