Diagnosing Multiple Faults in Dynamic Hybrid Systems

Imtiez Fliss and Moncef Tagina

Abstract. Due to their quite complex nature, Dynamic Hybrid Systems represent a constant challenge for their diagnosing. In this context, this paper proposes a general multiple faults model-based diagnosis methodology for hybrid dynamic systems characterized by slow discernable discrete modes. Each discrete mode has a continuous behavior. The considered systems are modeled using hybrid bond graph which allows the generating of residuals (Analytical Redundancy Relations) for each discrete mode. The evaluation of such residuals (detection faults step) extends previous works and is based on the combination of adaptive thresholdings and fuzzy logic reasoning. The performance of fuzzy logic detection is generally linked to its membership functions parameters.Thus, we rely on Particle Swarm Optimization (PSO) to get optimal fuzzy partition parameters. The results of the diagnosis module are finally displayed as a colored causal graph indicating the status of each system variable in each discrete mode. To make evidence of the effectiveness of the proposed solution, we rely on a diagnosis benchmark: The three-tank system.

1 Introduction

With the spread and the omnipresence of the dynamic hybrid systems, there is a great need for more efficiency, safety and reliability of these systems. The need for diagnostic tools is then crucial in this case as it is a key technology guaranteeing these criteria. In fact, correct and timely diagnosis helps the operator to take the adequate corrective actions in time. Diagnosis is the process of detecting an abnormality in the system behavior and isolating the cause or the source of this abnormality. This problem is more complex in case of multiple occurrences of faults. However, this case should be taken into account, as the performance of physical processes is

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affected by the presence of a single fault and is severely affected in case of multiple faults. In this context, this paper deals with the diagnosis of multiple faults in dynamic hybrid systems. These systems are characterized by the exhibition of both continuous and discrete dynamic behaviors. In this work, we consider hybrid systems whose dynamic evolution is described through the succession of a number of slow discernable discrete modes[4]. Each mode is characterized by a continuous evolution of its states. The transition from one mode to another occurs when a number of constraints are checked. Faults can affect either the sequence of discrete states or the continuous behavior in each discrete mode. In this paper, we focus in the diagnosis of multiple faults affecting the continuous behavior in each discrete mode of the dynamic hybrid systems. In this context, we propose to extend previous work [8]dealing with diagnosing multiple faults in continuous systems to dynamic hybrid systems. The proposed approach relies on the extension of Analytical Redundancy Relations (ARRs), a well known residual generating approach used in continuous systems, into hybrid plants inspired from [4]. In this case, we calculate to each discrete mode the corresponding ARRs. ARRs are symbolic equations representing constraints between different known process variables (parameters, measurements and sources). The evaluation of such residuals is done using the combination of adaptive thresholdings and fuzzy logic detection. The performance of fuzzy detection is closely linked to the fuzzy membership functions. For efficiency, an optimal design of membership functions is desired[9]. Thus, we choose to use an optimization technique to adjust the parameters of the fuzzy partitions: the Particle Swarm Optimization (PSO) [3]. The result of detection step is then presented as a colored causal graph. This result is then used in the isolation step which relies on the causal reasoning and gives final findings to the operator helping him to make proper corrective actions. To test the performance of the proposed approach, we rely on a simulation of a benchmark in the diagnosis domain: the three- tank hydraulic system. The remainder of this paper is organized as follows: section two details the proposed approach. While, the third section presents and discusses the simulation results we get, the fourth section points out our contribution to the literature. Finally, some concluding remarks are made.

2 The Proposed Approach for Diagnosing Multiple Faults in Dynamic Hybrid Systems

The diagnosis result indicates whether the system is normally functioning or there are some single or multiple faults that occur. In this work, the considered systems are dynamic hybrid systems characterized by the evolution of m slow discernable discrete modes. Each i mode {i in {1,.., m}} has a continuous evolution of possible configurations. The faults that can affect such systems are either caused by inadequate evolution of discrete modes or by the continuous behavior of each discrete mode. We concentrate, in this paper, on faults affecting the continuous behavior of system variables in each discrete mode. The aim of our work, consists, first of all, in detecting the presence of faults. Such a step results in deciding if each continuous behavior of each mode is faulty or not regardless of disturbances. To get this decision, we rely on the comparison of the system behavior to a reference model. This model should respect the particularities of the dynamic hybrid system to be diagnosed. A best manner to model systems is to use a hybrid bond graph [18] which has the pros of bond graph modeling [5] and introduces the mode switching thanks to the use of Switching elements (Sw) which evolution is described as a finite state sequential automata. The result of this comparison is called residuals. To generate these residuals, several approaches can be used:parity relations [12], state estimation [15], and methods based on parameter identification [11]. In this work, we drew inspiration from the work of Cocquempot et al. [4], which defines an extension of Analytical redundancy relations for each system mode as shown in fig.1.

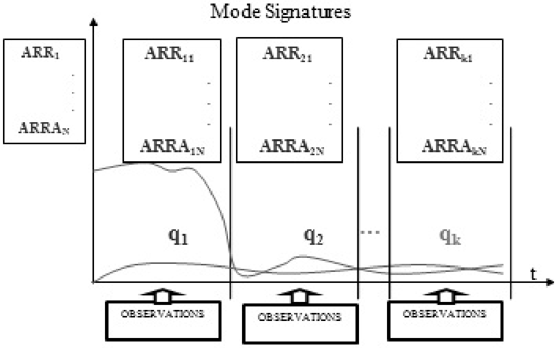

Fig. 1 Extension of Analytical Redundancy Relations for Hybrid systems [10]

For each discernable discrete mode, we generate corresponding residuals thanks to the use of bond graph modeling through the use of the procedure described in [21]. Then for each discrete mode, an evaluation of the system behavior is provided. The architecture of the whole proposed approach is described in fig.2.

In this step, we rely on previous works[8] which consists first of all in evaluating residuals using the Hôfling's adaptive thresholdings [14]. The result of such method is not too robust to disturbances, thus, we integrate the use of fuzzy logic reasoning considered as the best framework dealing with disturbances and uncertainties. Fuzzy logic fault detection consists in interpreting the residuals by generating a value of belonging to the class AL (Alarm) between 0 and 1 that allows one to decide whether the measurement is normal or not. The gradual evolution of this variable from 0 to 1 represents the evolution of the variable to an abnormal state [7]. In practical cases, fuzzy logic effectiveness is closely linked to its partitions parameters. So, to get the best results, optimal values of these parameters should be used. In this context, we rely on Particle Swarm optimization technique, which is characterized by an easy implementation and no gradient information requirement. There have been several versions of Particle Swarm Optimization. We choose in our research one

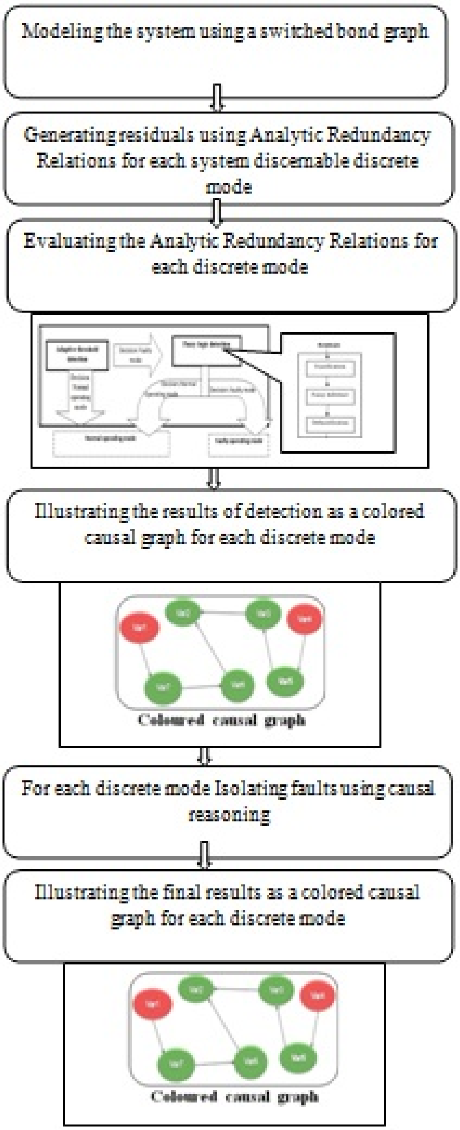

Fig. 2 The proposed approach

of the basic versions as they focus on cooperation rather than competition and are characterized by no selection:the PSO version with constriction factor. This version is also characterized by its speed of convergence [3].

For each discrete mode, the results of the detector combining the adaptive thresholdings and the fuzzy reasoning are displayed as a causal graph whose nodes are either red (suspected to be faulty) or green (normally functioning). Once at least one fault is detected, the isolation procedure is activated. This procedure is based on the causal graph reasoning and consists in looking for the source or the cause of the single or multiple detected faults. The details of such a reasoning are given in [6]. Finally and in order to assist the operator to make the proper corrective actions, the results are summed up as a colored causal graph.

3 Application of the Proposed Approach to an Industrial Process

The proposed solution is tested on a simulation of the three- tank hydraulic system.

3.1 Process Description

The considered hybrid process, shown in fig. 3, consists of three cylindrical tanks (Tank1, Tank2 and Tank3) that can be filled with two identical, independent pumps acting on the outer tanks 1 and 2.Tanks communicate through feeding valves that can assume either the completely open or the completely closed position. Pumps are controlled through on/off valves. The total number of valves is six. The liquid levels h1, h2, h3 in each tank represent continuous valued variables. The flow liquid rate from tank i to tank j is given by the following formula:

$$Q_{ij} = a_z \times S \times sgn(h_i - h_j) \times \sqrt{2 \times g \times |h_i - h_j|} \tag{1}$$

Where:

- hi (measured in meters) is the liquid level of tank i for i=1, 2, 3, respectively.
- az the outflow coefficient.
- S is the sectional area of the connecting valve.
- g the gravitational constant.

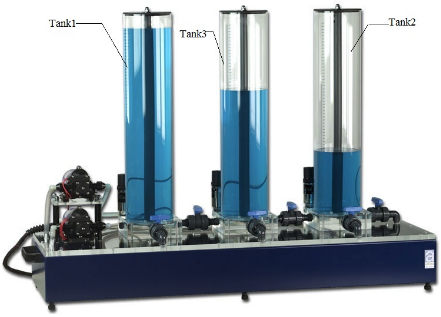

Fig. 3 The three-tank system [1]

The global purpose of the three- tank system is to keep a steady fluid level in the Tank 3, the one in the middle. A first step of our work concerns the modeling of the considered system. Thus, and as we previously mentioned, we rely on hybrid bond graph.

3.2 The System Hybrid Bond Graph Model

The hybrid bond graph model of the three- tank system is giving in fig.4. The tanks are modeled as capacitances and the valves are modeled as resistances. Msf1 and Msf2 correspond to flows volume applied to the system. 0- and 1- junctions represent respectively the common effort and common flow. The switching 1i-junctions represent idealized discrete switching element that can turn the corresponding energy connection on and off. These switching junctions are specified as a finite state sequential automata.

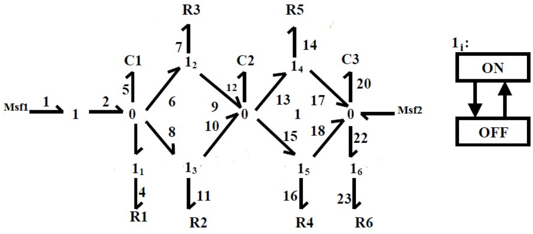

Fig. 4 The three-tank system Hybrid Bond Graph model

The levels of fluid in the tanks are all governed by continuous differential equations. These equations change as the valve configurations change. Then, a specific valve configuration determines the mode of the system. Since there are six valves, there are 64 total modes of the system. Each mode is governed by a different set of Analytic Redundancy Relations. For each mode of the three-tank system, the generation of Analytic Redundancy Relations is done directly from the bond graph model based on the procedure described in [21] and [9].

3.3 Experimental Results

The proposed approach was implemented on the three-tank hydraulic system in order to evaluate its performance. In this context, we considered as a first step forty discernable discrete modes whose evolution is given in fig.5. We performed a series of more than one hundred- forty tests (by injecting single and multiple faults) for several system functioning modes. At each test scenario, we checked if proper decision is finally given. The Simulation results we get are summed up in the following figures (fig. 6, fig.7 and fig. 8), knowing that the decision has the value of 1 in case of correct decision and 0 otherwise. According to simulation results (fig. 8) and

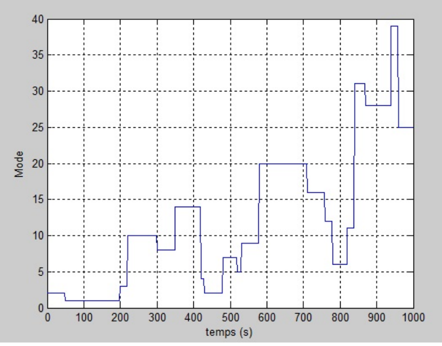

Fig. 5 Discrete modes evolution

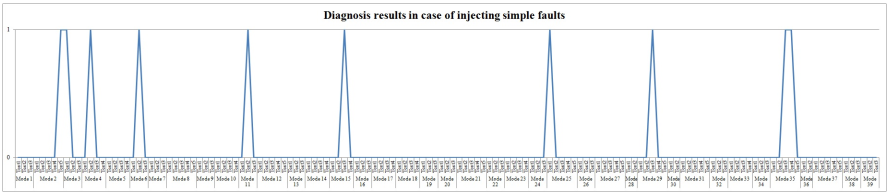

Fig. 6 Results in case of injecting simple faults

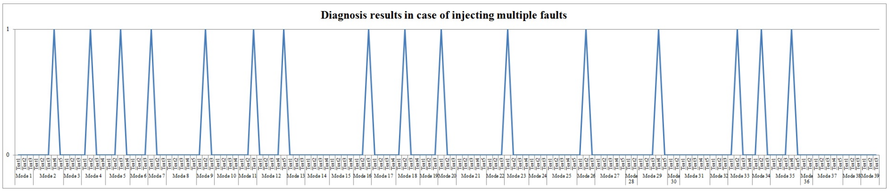

Fig. 7 Results in case of injecting multiple faults

the preliminary result got in [10], the proposed approach gives promising diagnosis results. In fact, it gives the correct decision in almost 88 % of tested cases. This result is obtained thanks to the combination of the use of adaptive thresholdings and fuzzy logic optimized by Particle Swarm Optimization technique. In fact, according to the results we get, the integration of these two detection techniques overcomes the limitations of individual strategies of each method and ameliorate significantly the diagnosis result. This can also explain by the use of causal reasoning in the localization step which analyzes the propagation paths in the graph to determine whether fault hypotheses are sufficient to account for other secondary faults, resulting from its propagation in the process over time. Then, only variables that are really faulty are announced defective [6]. The proposed approach provides us also with a representative results facilitating the operator's decision making thanks to use of colored causal graph displaying the systems variables state. For instance, in case of injecting

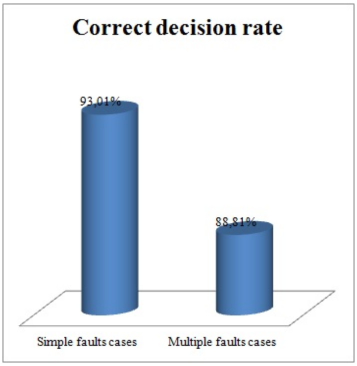

Fig. 8 Correct diagnosis rates

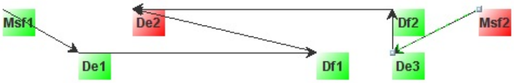

Fig. 9 Result of injecting {De2and Msf2} using the proposed diagnosing approach

multiple faults in De2 and Msf2 in the discrete mode in which all valves are in on functioning mode, the final findings are shown in fig.9.

4 Related Works and Discussion

A literature review shows that there are several approaches addressing the diagnosis of dynamic hybrid systems problem[2,13,16,17,19,20,22,23] based on extension of continuous systems approaches. We generally find two diagnosing options: works based on residual generation techniques and others based on causal reasoning. For instance, in [19], authors present a diagnosis methodology based on the use of a hybrid observer to track system behavior. The observer uses the state equations models for tracking continuous behavior in a mode, and hybrid automata for detecting and making mode transitions as system behavior evolves. Detection of mode changes requires access to controller signals for controlled jumps, and predictions of state variable values for autonomous jumps. If a mode change occurs in the system, the observer switches the tracking model (different set of state space equations), initializes the state variables in the new mode, and continues tracking system behavior with the new model. The fault detector compares the observations from the system and the predictions from the observer to look for significant deviations in the observed signals. In the same option, authors in[17] present a novel approach to monitoring and diagnosing real-time embedded systems that integrates model-based techniques using hybrid system models with distributed signature analysis. They present a framework for fault parameterization based on hybrid automata models.

The developed model is used to generate the fault symptom table for different fault hypotheses. The fault symptom table is generated off-line by simulation and is compiled into a decision tree that is used as the on-line diagnoser. The model compares observed sensor events with their expected values. When a fault occurs, the deviation from the simulated behavior triggers the decision-tree diagnoser. The diagnoser either waits for the next sensor event or queries the mode estimator to search for a particular event, depending on the next test. This approach has the advantage of detecting faults due to the continuous variables and the occurrence of disruptive events. In [4] the well known parity space approach is extended to hybrid systems in order to identify on-line the current mode and to estimate the switching instants. The fault detection consists in generating residuals between the input variables and measured outputs and analytical redundancy relations determined from the inputs and the outputs as well as their derivations, independently of the system discrete mode. The structured residuals are used to determine the current mode and to detect continuous and discrete faults. On the other hand, qualitative modeling by causal graph is proposed in [13] through a representation based on hybrid continuous causal Petri nets (HC2PN). Causal links (transitions) between continuous variables (the places) are represented through quality transfer functions quality (QFT) based on information on Gain (K), late (r) and time constant (r) (transitions). The evolution of the input variables and the qualitative response (QR) are at a QFT approximated by a piecewise affine function via a segmentation procedure. Each segment is called an episode. Crossing speed of a transition (change of marking) is a function of constant time piecewise, depending on the detected episodes, on the evolution of the marking of the upstream place and parameters of the QFT. The model HC2PN is then integrated into supervisor modeled by a Petri Nets through an interface event, forming a structure similar to Petri net models of Hybrids and monitoring approaches. The system fault detection, influencing continuous variables, is carried out asynchronously; fault location is performed by chaining backward / forward causal links between variables by using their temporal characteristics. Another approach based on causal reasoning has been proposed in [16]. This approach is based primarily on modeling the system by a hybrid bond graph model and then generates a graph of faults propagation, which can describe the temporal and causal relationships between different faults modes on one side, and observations related to another. This approach integrates the use of failure-propagation graph-based techniques for discrete-event diagnosis and combined qualitative reasoning and quantitative parameter estimation methods for parameterized fault isolation of degraded components (sensors, actuators, and plant components).

Unlike these works, the major contribution of our work consists in detecting and localizing multiple faults in dynamic hybrid systems using both generating residual reasoning and causal reasoning. In fact, we rely in the detection step on the generation of analytical redundancy relations (ARRs) in each discrete discernable mode. These ARRs are generated through the using of hybrid bond graph and are evaluated using a combination of adaptive thresholdings and fuzzy logic optimized using PSO. Exploiting fuzzy reasoning allows us to get the most accurate decision even if residuals are affected by the noise contamination and uncertainty effects. On the other hand, the results of detection step are summed up as a colored causal graph which is used in the isolation step. Indeed, isolation step consists in generating a causal propagation reasoning. As it uses a backward/forward procedure starting from an inconsistent variable localized as a faulty node: red node in the generated colored causal graph. The use of colored causal graph to display the diagnosis results facilitates the operator's understandings and helps him to make adequate corrective actions in time.

5 Conclusion

This paper addresses the problem of multiple faults in dynamic hybrid systems. These systems are assumed to have slow discernable discrete modes characterized by continuous behaviors.The continuous behaviors could be affected by single or multiple faults. Thus, we propose, in this paper, a general approach to diagnose single and multiple faults in dynamic hybrid systems relying on extension of previous works dealing with continuous systems. The proposed approach exploits the performance of combining adaptive thresholdings and fuzzy logic reasoning optimized using Particle Swarm Optimization. Experiments are based on the case of the hybrid dynamic system: three-tank hydraulic system, considered as a benchmark in the diagnosis field. They have proven the efficacy of the proposed approach. We intend in future work to consider faults affecting the discrete mode evolution of dynamic hybrid systems

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