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Hybrid system diagnosis: Test of the diagnoser HYDIAG on a benchmark of the international diagnostic competition DXC'2011

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Abstract: Estimating the health status of the components forming a hybrid system means to account for interleaved continuous and discrete dynamics. It is the task of the diagnoser to infer this status from a partial set of observations and a mathematical model of the physical system. Whereas most of the approaches adopt a state estimation scheme, the HYDIAG diagnoser is based on an extension of the parity space method to hybrid systems together with an event based abstraction of the continuous dynamics that permits to cast the diagnosis problem in the discrete event systems framework. This paper aims at testing the HYDIAG diagnoser on the realistic test case ADAPT provided by NASA Ames in the form of a benchmark which is proposed for the diagnosis competition of the DX community.

Keywords: Hybrid systems, Model-based diagnosis, NASA ADAPT, embedded systems.

1. INTRODUCTION

The development of recent systems exhibits a high complexification of behaviours. This implies two problems. Firstly, most of the systems are hybrid: they present both continuous and discrete behaviours. A specific formalism has to be adopted in order to describe them. Secondly, systems are exposed to component failures. Maintenance and repair are an increasing part of the total cost of final product. Efficient diagnosis techniques have to be adopted to detect and isolate faults. In particular for hybrid systems, the HYDIAG diagnoser (Bayoudh (2009)) is a solution to estimate the current mode of operation/failure, leaving implicit the continuous evolution of the hybrid system.

The comparison of diagnosis technologies is known to be difficult because of the difficulty to build simple enough but still realistic benchmarks. However, a diagnosis competition has been conjointly defined by NASA Ames Research Centre, Palo Alto Research Centre and Delft University of Technology during the 20^{th} International Workshop on Principles of Diagnosis (DX-09). The goal is to propose a generalized framework to compare and evaluate diagnosis algorithms (Kurtoglu et al. (2009)), using real-world system data. We propose to use HYDIAG in this context and to test it under the industrial track problem DP-I (DXC'11 (2011)), using the Electrical Power System test bed in the ADAPT lab at the NASA Ames Research Centre. There exist few papers on the results of the competitions. (Daigle and Roychoudhury (2010)) is one of them, and we will compare our results to it.

The paper is organized as follows. Section 2 overviews the hybrid model supporting diagnosis in HYDIAG. Section 3 describes the diagnoser HYDIAG. Section 4 presents the DP-I industrial track problem and reports the results. Section 5 concludes this paper.

2. HYBRID MODEL FOR DIAGNOSIS

The modelling framework that is adopted is based on a hybrid automaton (Henzinger (1996)). The hybrid automaton is defined as a tuple $S = (\zeta, Q, \Sigma, T, C, (q_0, \zeta_0))$ where:

- ζ is the set of continuous variables that comprises input variables $u(t) \in R^{n_u}$, state variables $x(t) \in R^{n_x}$, and output variables $y(t) \in R^{n_y}$. The set of directly measured variables is denoted by ζ_{OBS}.
- Q is the set of discrete system states. Each state $q_i \in Q$ represents a behavioural mode of the system. It includes nominal and anticipated fault modes. The anticipated fault modes are fault modes that are known to be possible on the system. The unknown mode defined in (Hofbaur and Williams (2004)) can be added to model all the non anticipated faulty situations.
- Σ is the set of events that correspond to discrete control inputs, autonomous mode changes and fault occurrences. $\Sigma = \Sigma_{uo} \cup \Sigma_o$, where $\Sigma_o \subseteq \Sigma$ is the set of observable events and $\Sigma_{uo} \subseteq \Sigma$ is the set of unobservable events.
- $T \subseteq Q \times \Sigma \to Q$ is the partial transition function. The transition from mode q_i to mode q_j with associated event σ_{ij} is noted $t(q_i, \sigma_{ij}, q_j)$ and we have $T(q_i, \sigma_{ij}) = q_j$. T also denotes the set of transitions.
- $C = \bigcup_i C_i$ is the set of system constraints linking continuous variables. C_i denotes the set of constraints

associated to the mode q_i. C represents the set of differential and algebraic equations modelling the continuous behaviour of the system. The continuous behaviour in each mode is assumed to be linear.

- $(\zeta_0, q_0) \in \zeta \times Q$, is the initial condition.

The occurrence of a fault $F_i \in F$ is modelled by a discrete event $f_i \in \Sigma_F$. Σ_F is the set of fault events associated to the anticipated faults of F. Without loss generality it is assumed that $\Sigma_F \subseteq \Sigma_{uo}$. The discrete part of the hybrid automaton is given by $M = (Q, \Sigma, T, q_0)$, which is called the *underlying discrete event system (DES)* and the continuous behaviour of the hybrid system is modelled by the so called *underlying multimode system* $\Xi = (\zeta, Q, C, \zeta_0)$.

3. OVERVIEW OF THE HYDIAG DIAGNOSER

The method developed in (Bayoudh (2009), Bayoudh et al. (2008)) for diagnosing faults on-line in hybrid systems can be seen as interlinking a standard diagnosis method for continuous systems, namely the parity space method, and a standard diagnosis method for DES, namely the diagnoser method (Sampath et al. (1995)). This section presents an overview of the diagnoser.

3.1 Diagnoser's inputs

Hydiag takes as input an hybrid automaton S as illustrated in figure 1.

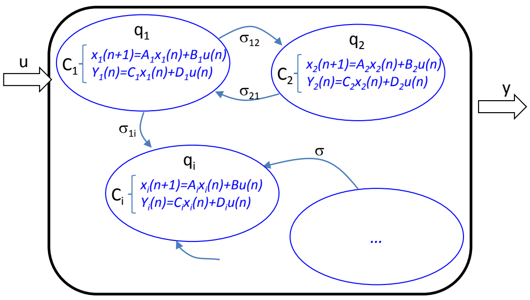

Fig. 1. Example of an hybrid system

After the development of the hybrid diagnoser, Hydiag needs on-line the set of observations on the system.

3.2 Mode Signature

Consistency tests take the form of a set of analytical redundancy relations (ARR). For the linear case, it is possible to computes ARRs by using the parity space approach (Staroswiecki and Comtet-Varga (2001)). This approach has been recently extended to multimode systems in (Cocquempot. et al. (2004)). In our case, an ARR set is associated to each mode q_i and is denoted ARR_i. An ARR_{ij} can be expressed as $r_{ij} = 0$, where r_{ij} is called the residual of the ARR. Since ARRs are constraints that only contain observable variables, they can be evaluated on line with the incoming observations given by the sensors, allowing to check the consistency of the observed system behavior against the predicted one. ARRs are satisfied if the observations satisfy the model constraints, in which case the associated residuals are zero. In the opposite case, all or some residuals may be non zero. The set of residuals in mode q_i hence result in a local boolean fault indicator tuple.

$$r_{ij} = \begin{cases} 0 \text{ when } ARR_{ij} \text{ is satisfied} \\ 1 \text{ otherwise} \end{cases}$$

$j = 1, ..., N_{ARR(q_i)}$, where $N_{ARR}(q_i)$ is the number of ARRs/residuals associated to mode q_i.

Due to the fact that there are different modes, we need to define the vector of residuals of mode q_k computed with the observations ζ^j_{OBS} obtained when the system is in mode q_j. This vector is called the q_k-mirror signature of mode q_j. It is the signature of mode q_j seen in mode q_k.

Definition 1. (Mirror Signature). Given the vector $R_k = [r_{k1}, r_{k2}, ..., r_{kN_{ARR(q_k)}}]^T$ of system residuals in mode q_k, the q_k-mirror signature of mode q_j is given by the vector $S_{j/k} = [s_{1_{j/k}}, ..., s_{N_{ARR(q_k)_{j/k}}}]^T = [R_k(\zeta^j_{OBS})]^T$.

Definition 2. (Mode Signature). The mode signature of a mode q_j is the vector obtained by the concatenation of all its mirror signatures:

$$Sig(q_j) = [S^T_{j/1}, S^T_{j/2}, ..., S^T_{j/j}, ..., S^T_{j/m}]^T.$$

3.3 Diagnosability group

Since residuals have been designed for every mode separately and that there exists noise, this may cause false alarm problems. For solving this problem, Hydiag uses an on-line residual filter that takes as input the residual values and generates as output clean boolean indicators. Two modes q_i and q_j, $(q_i, q_j) \in Q^2$ are diagnosable if their continuous dynamics defined by the state-space matrices A_i, B_i, C_i, D_i and A_j, B_j, C_j, D_j are sufficiently distinct so that their cleaned residuals are not identical i.e. their mode signatures are different. If two modes are not diagnosable, it means that they belong to the same diagnosability group. Otherwise, the two modes are merged into the same group.

3.4 Event based abstraction of the continuous dynamics

The idea of HYDIAG is to capture both the continuous dynamics and the discrete dynamics within the same mathematical object. To do so, the original automaton of the hybrid system $M = (Q, \Sigma, T, q_0)$ is enriched with specific observable events that are generated from the mode signatures. A specific transition labelled with a specific *signature-event* is introduced between two modes when they have different mode signatures. The change of signature triggers the occurrence of the associated signature-event. The resulting automaton is called the *Behaviour Automaton* (BA) of the hybrid system.

3.5 Building the "hybrid" diagnoser

Diagnosis is performed thanks to a specific finite machine called a *diagnoser*. The diagnoser is built from the BA following the approach described in (Sampath et al. (1995)). The task of building such diagnoser is not easy because it requires to browse the entire graph representing the BA automaton. To this end, the tool DiaDES [1] from LAAS,

[1] http://www.laas.fr/ ypencole/DiaDes