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INCREASING EFFECTIVENESS OF MODEL-BASED FAULT DIAGNOSIS:
A DYNAMIC BAYESIAN NETWORK DESIGN FOR DECISION MAKING

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Abstract: This paper aims to design a new approach in order to increase the performance of the decision making in model-based fault diagnosis when signature vectors of various faults are identical or closed. The proposed approach consists on taking into account the knowledge issued from the reliability analysis and the model-based fault diagnosis. The decision making, formalised as a Bayesian network, is established with a priori knowledge on the dynamic component degradation through Markov chains. The effectiveness and performances of the technique are illustrated on a heating water process corrupted by faults. Copyright © 2006 IFAC

Keywords: Model-based fault diagnosis, Bayesian Networks, Reliability, Markov chains, Decision making.

1. INTRODUCTION

A large diversity of advanced methods for automated Fault Detection and Isolation (FDI) exists based on the fault diagnosis principle. Faults in systems are usually diagnosed using analytical redundancy when comparing measured and estimated outputs of the system. A short historical view on FDI can also be found in (Isermann and Ballé, 1996) and current developments can be observed in (Patton et al., 2000). The diagnosis procedure is composed of three stages: residuals generation, residuals evaluation and finally decision making.

Classically, decision making is realized according to an elementary logic. Nevertheless, when multiple faults or false alarms occur, the faults can not be isolated (Korbick, et al., 2004). Some specific mathematics algorithms can improve the efficiency of the decision making, for instance:

- (Gertler, 1998), (Chen and Patton, 1999), have proposed methods based on the principle of disturbance decoupling to increase the robustness of the residuals generation;
- (Sauter et al., 1993) have developed a method based on adaptive threshold approach to reduce the sensitivity of the residuals evaluation against false alarms.

However, in any cases the binary data produced by residuals evaluation are poor in information, consequently some other knowledge related to the residuals can be considered for isolation. (Theilliol et al., 1995) and (Evsukoff and Gentil, 2005) shows that it can be useful to combine qualitative and quantitative knowledge to improve the fault diagnosis efficiency. In the spirit of (Isermann, 1994), fault isolation performance can increase through the integration of other knowledge in the diagnosis procedure.

Thus, reliability analyses classically computed by means of stochastic process model as Markov Chains (MC) define the a priori behavior of the probabilities distribution over the functioning and mal-functioning states of the system. Also this additional information is seldom used to improve decision making in model-based fault diagnosis (Anrig and Kohlas, 2002). The aim of the paper is to propose a new approach in order to increase the performance of the decision making in fault diagnosis by taking into account a priori knowledge of the system state through the dynamic Bayesian network.

Table 1. Incidence matrix example

<table>
<thead>
<tr>
<th></th>
<th>$F_1$</th>
<th>$F_2$</th>
<th>$F_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_1$</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$u_2$</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$u_3$</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

In this table, a “1” denotes that a symptom $u_i$ is sensitive to a fault ($F_i, F_j$ or $F_k$), while a “0” denotes insensitivity. This table is called an incidence matrix and can be considered as an a priori knowledge. Each column of the incidence matrix represents a fault signature: the vector $[0 1 1]^T$.

The paper is organized as follows: Section 2 is dedicated to recall the decision making in model-based fault diagnosis and fault isolation problem is stated. Section 3 explains the method to perform the decision making with the Bayesian network (BN) inference and is also devoted to the design of our solution to merge the FDI and the dynamic reliability. The proposed approach is illustrated through a simulation example in Section 4. Finally, conclusions and perspectives are presented in last Section.

2. PROBLEM STATEMENT

2.1 Symptoms generation

Usually, the second step of the diagnostic procedure, Residuals evaluation, is based on the assumption that if a fault occurs, the statistical characteristic of the residuals is modified. The residuals evaluation involves statistical testing such as limit checking test, generalized likelihood ratio test, trend analysis test. The output vector of the statistical test, called coherence vector $U$, can be built according to a test applied to a set of $J$ residuals: $U = [u_1, ..., u_j, ..., u_J]$ where $u_j$ represents the status of the residuals: $u_j$ is equal to “0” when the residual signal is closed to zero in some sense and equal to “1” otherwise. $u_j$ is called the symptom associated to the residual $r_j$.

2.2 Incidence matrix

While a single residual is sufficient to detect a fault, a set of evaluated residuals is required for fault isolation. Several approaches have been suggested to generate structured residuals and consequently incidence matrix (Frank, 1990).

As a simple example, three different faults ($F_1$, $F_2$ and $F_3$) can be isolated by designing three symptoms ($u_1$, $u_2$ and $u_3$) using the following table:

Table 1. Incidence matrix example

<table>
<thead>
<tr>
<th></th>
<th>$F_1$</th>
<th>$F_2$</th>
<th>$F_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_1$</td>
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<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$u_2$</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$u_3$</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

In this table, a “1” denotes that a symptom $u_i$ is sensitive to a fault ($F_i, F_j$ or $F_k$), while a “0” denotes insensitivity. This table is called an incidence matrix and can be considered as an a priori knowledge. Each column of the incidence matrix represents a fault signature: the vector $[0 1 1]^T$.
corresponds to the signature of the faulty element $F_i$. In this paper, incidence matrix is annotated $D$ with different elements $D(n,j)$ where $n$ is the number of elements suspected to be faulty ($n=1...N$) and $j$ is the number of residuals ($j=1...J$).

2.3 Fault Isolation

Usually, a very simple logic test between each fault signature and each coherence vector is used to isolate the faulty component. In practical cases false alarms occur and corrupt the logic decision. The coherence vector can be different from all signatures. Therefore, the goal of decision making is to minimize the false alarms and missing alarm rates due to the effects of modelling uncertainties and unknown disturbances that affect the residuals. Moreover, in spite of the robustness of residuals generation and evaluation, a simple logic rule is not efficient enough to isolate faults when simultaneous multiple faults occur (Weber et al., 1999). This is justified by the fact that if $D(n,j)=0$, then $u_i$ cannot bring any information about the occurrence of fault $F_n$, because the residual $r_j$ might be different from 0 due to noise or modelling errors or another fault $F_k$ (with $D(k,j)=1$) affecting the system. Notice that, in spite of using a fault indicator or a better integration of residual generation in diagnostic decision, as demonstrated by (Combastel et al., 2003) the effectiveness of the decision making in FDI scheme can not be improved. Thus, the reliability analysis for the fault diagnosis has been recently proposed by (Boniventi et al., 2003). Therefore, a new source of information should be integrated in FDI procedure. System reliability analysis allows to determine the degree of degradation of the system components. The paper aims to develop a method in order to integrate a dynamic reliability estimation of the system component with the objective of increasing the quality of information taking into account to achieve an efficient decision making.

3. DECISION MAKING DESIGN

3.1 Bayesian network equivalent to incidence matrix

a) Bayesian Network: BN are probabilistic networks based on graph theory. They are directed acyclic graphs used to represent uncertain knowledge in Artificial Intelligence (Jensen, 1999). Each node represents a discrete variable defined over several states and the arcs indicate direct probabilistic relations between the nodes. Thus a discrete random variable $X$ is represented by a node $n$ with a finite number of mutually exclusive states. States are defined on $S_n = \{s_1^n,...,s_{M_n}^n\}$. The vector $p(n)$ denotes a probability distribution over these states, and $p(n=s_m^n)\ (\forall m \in [1,...,M])$ is the marginal probability of $n$ being in state $s_m^n$. In the graph depicted in Figure 1, nodes $n_i$ and $n_j$ are linked by an arc, $n_i$ is considered as a parent of $n_j$.

![Figure 1: Elementary Bayesian network](image)

A conditional probability distribution quantifies the probabilistic dependency between $n_j$ and its parent $n_i$ and is defined through a Conditional Probability Table (CPT). Therefore, the nodes $n_i$ and $n_j$ are defined over the sets $S_{n_i} = \{s_1^{n_i},...,s_{M_{n_i}}^{n_i}\}$ and $S_{n_j} = \{s_1^{n_j},...,s_{M_{n_j}}^{n_j}\}$. The CPT of $n_j$ is then defined by the conditional probabilities $p(n_j | n_i)$ over each $n_j$ state according to its parents $n_i$ states as presented in the following table:

Table 2 : Conditional Probability Table for $n_j$

<table>
<thead>
<tr>
<th>$n_i$</th>
<th>$n_j$</th>
<th>$s_1^{n_j}$</th>
<th>...</th>
<th>$s_{M_{n_j}}^{n_j}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s_1^{n_i}$</td>
<td>$p(n_j=s_1^{n_j}</td>
<td>n_i)$</td>
<td>...</td>
<td>$p(n_j=s_{M_{n_j}}^{n_j}</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>$s_1^{n_i}$</td>
<td>$p(n_j=s_1^{n_j}</td>
<td>n_i)$</td>
<td>...</td>
<td>$p(n_j=s_{M_{n_j}}^{n_j}</td>
</tr>
</tbody>
</table>

Concerning the root nodes, i.e. those without parent, the CPT contains only a row describing the a priori probability of each state. Various inference algorithms can be used to compute marginal probabilities for each unobserved node given information on the states of a set of observed nodes. The most classical one relies on the use of a junction tree. Inference in BN then allows to take into account any state variable observation (an event) so as to update the probabilities of the other variables. Without observation, the computation is based on a priori probabilities. When observations are given, this knowledge is integrated into the network and all the probabilities are updated. Knowledge is formalised as evidence. A hard evidence of the random variable $X$ indicates that the state of the node $n$ is one of the states $S_n = \{s_1^n,...,s_{M_n}^n\}$. For instance $X$ is in state $s_1^n: p(n=s_1^n) = 1$ and $p(n=s_{M_n}^n) = 0$. Moreover, when this knowledge is uncertain, soft evidence can be used to define the distribution over $n$.

![Figure 2 : Bayesian network structured](image)
defined over the set of two states: \{not detected, detected\} with \(p(s_j=\text{detected})\), if the fault affects the system and the residual \(r_j\) is detected different from 0.

The probability distribution over the symptoms states depends on the false alarms and missing detections. Using BN model, a CPT is used to model the relation among variables. To compute the symptoms \(u_i\) distribution of probability, a CPT is defined according to the fault \(F_i\) parent of \(u_i\). For instance, when only one symptom is associated to one fault, as presented in Figure 2a, then the CPT has the following structure:

\[
\begin{array}{ccc}
F_u & u_i & \\
\text{not occurred} & 1 - c_n & c_n \\
\text{occurred} & b_n & 1 - b_n
\end{array}
\]

where

\[
b_n = p(u_i = \text{not detected}|F_u = \text{occurred})
\]

\[
c_n = p(u_i = \text{detected}|F_u = \text{not occurred})
\]

In other words, \(b_n\) defines the probability of missing detection for the fault \(F_u\); \(c_n\) the probability of false alarms for the fault \(F_u\). Generally, there are several faults associated to one symptom; as presented in Figure 2b. In this case, the CPT is a more difficult to obtain. As presented in Table 4, generated according to the incidence matrix defined in Figure 2b, \(p(u_i|F_u,F_x)\) is defined according to the miss detection \(b_1\) (resp. \(b_0\)) and the false alarm \(c_1\) (resp. \(c_0\)) for the fault \(F_1\) (resp. \(F_0\)).

<table>
<thead>
<tr>
<th>(u_i)</th>
<th>(F_u)</th>
<th>not detected</th>
<th>detected</th>
</tr>
</thead>
<tbody>
<tr>
<td>not occurred</td>
<td>1 - (c_n) &amp; (c_n)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>occurred</td>
<td>(b_n) &amp; 1 - (b_n)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In the framework of decision making, we considered a discrete random variable \(X\) with two states \{up, down\} for the sake of simplicity. These states represent respectively the operational and failure state of the component. Associated to a discrete random variable \(X\), a matrix \(P_X\) defines the probabilistic state transitions between \(\text{up}\) and \(\text{down}\):

\[
P_X = \begin{bmatrix}
1 - p_{du} & p_{du} \\
p_{du} & 1
\end{bmatrix}
\]

Where \(p_{du}\) represents the failure probability of the component between sample \((k-1)\) and \((k)\)

\[
p_{du} = p(X_k = \text{down}|X_{k-1} = \text{up})
\]

In reliability analysis, \(\lambda\) represents the failure rate of the component with \(p_{du} = \lambda \times \Delta k\) where \(\Delta k\) represents the time interval between \((k-1)\) and \((k)\). It can be reminded that for a constant failure rate, the Mean Time To Failure (MTTF) is equal to \(1/\lambda\). Based on this elementary definition, a discrete-time Markov chain is defined when the initial state probability vector is specified \(p(X_0) = [p(X_0 = \text{up}) \ p(X_0 = \text{down})]\). The transient analysis of the MC based on the Chapman-Kolmogorov equation (Cassandras and Lafortune, 1999) provides an expression for \(p(X_k)\) with \(p(X_k) = (P_X)\) for \(k = 1, 2, \ldots\) Under dynamic consideration in a Bayesian network, the state of the \(i\)-th variable \(X_i\) is represented at sample \(k\) by a node \(n_k(k)\) with a finite number of states \(S_{n_k} = \{s_{n_k,0}, \ldots, s_{n_k,m}\}\). \(p(n_k(k))\) denotes the probability distribution over these states at time step \(k\). The Dynamic Bayesian Networks allow to represent random variables and their impacts on the future distribution of other variables (Weber and Jouffe 2003). Beginning from an observed situation at sample \(k=0\), the probability distribution \(p(n_k(k))\) over \(M\) states for the component \(X_i\) associated to the node \(n_k\) is computed by the Dynamic BN inference. Indeed, it is possible to compute the probability distribution of any variable \(X_i\) at sample \(k\) based on the probabilities defined at sample \(k-1\) as represented in the elementary network presented in Figure 5. The first slice contains the nodes corresponding to the current time step \((k-1)\), the second one those of the following time step \((k)\). Observations, introduced as hard evidence or probability distributions, are only realised in the current time slice. The time increment is carried out by setting the computed marginal probabilities of the node at sample \(k\) as observations for its corresponding node in the previous time slice. The CPT in DBN is defined equivalent to \(P_X\).

3.2 Dynamic model of reliability: a Dynamic BN solution

(Weber and Jouffe, 2003)

In order to model dynamic behaviour of the system degradation, Dynamic BN has been considered in our approach, let us recalled some fundamental Markov Chain (MC) model.

Figure 3 : Dynamic Bayesian Network for \(X_i\)

3.3 Fusion of the Incidence Matrix and the DBN: a solution for a decision making more efficient

As presented previously, the Dynamic BN models the component reliability which takes into account the time...
degradation of the component. The representation of Incidence Matrix as a graph, presented at the beginning of
the paper, provides a formalism to make the fusion between fault diagnosis and reliability model. The decision
making is made after fusion of information issued from the residual analyses and the reliability estimation. Therefore,
based on the BN representation, image of the incidence matrix, the dynamic evolution of the component reliability
is taken into account on the nodes \( F_i \) as presented in Figure 4. This relationship involves the definition of a CPT (see
Table 5). The CPT of \( F_i \) is very simple to define if the component is modelled with the states “up” or “down” which is a common case in fault diagnosis.

\[
P(F_i | u_1, u_2, n_i(k))
\]

The computation of \( p(F_i | u_1, u_2, n_i(k)) \) is performed thank to the inference algorithm in BN.

4. ILLUSTRATION EXAMPLE

4.1. Process description and fault diagnosis

To illustrate our approach, we proposed to consider a simulation example: a heating water process. The proposed
approach has been designed with the help of the software BayesiaLab (www.bayesia.com). The process, presented in
Figure 5, is composed of a tank equipped with two heating resistors \( R_1 \) and \( R_2 \). The inputs are the water flow rate \( Q_i \),
the water temperature \( T_i \) and the heater electric power \( P \). The outputs are the water flow rate \( Q_o \) and the temperature
\( T \) which is regulated around an operating point. The temperature of the water \( T_i \) is assumed to be constant. The
objective of the thermal process is to assure a constant water flow rate with a given temperature. In this analysis
only sensor and components failures are considered: level sensor \( H \), output temperature sensor \( T \) and output flow rate
sensor \( Q_o \). From model-based fault diagnosis, a classical observer scheme approach is considered. Based on a state
space representation of the system around an operating condition where output vector is equal to \([H \ T]^T\) and input
vector \([Q_i \ P]^T\), structured residual are generated and evaluated in order to detect when \( H \) level sensor or \( T \)
temperature sensor faults occur. Moreover according to the physical equation between output flow rate \( Q_o \) and liquid
level \( H \), other residual could be established, the fault incidence matrix is defined Table 6.

\[
\begin{array}{ccc}
H & Qo & T \\
\hline
u_1 & 0 & 0 & 1 \\
u_2 & 1 & 0 & 0 \\
u_3 & 1 & 1 & 0 \\
\end{array}
\]

The incidence matrix, defined in Table 6, leads to a corresponding DBN model presented in Figure 6. For all faults of the system, it is assumed that the probability of miss detection is fixed to 0.02 and the probability of false alerts is fixed to 0.05. Consequently presented in §3.1 the CPT of \( u_1 \); defined in Table 7 is deduced from Table 3, and also the CPT of \( u_3 \) (Table 8) from Table 4.

In order to defined the dynamic reliability model, Figure 7 to Figure 9 present the Mean Time To Failure (MTTF) to
determine the failure rates $\lambda$, which quantify the transition between the states of 3 considered faulty components and associated probabilistic state matrix $P_x$ defined in eq. (3). The Markov Chains of the components are supposed to be independent. It should be noted that two states \{up, down\} are considered for sensors Qo and H, but one more state \{dgd\} is considered for sensor T which corresponds to a degradation state of the component.

MTTF$_1$=45,000 h  
$\lambda_1=0.22 \times 10^{-4}$

Figure 7: Reliability MC model for sensor Qo.

MTTF$_1$=5,000 h  
$\lambda_1=2 \times 10^{-4}$

Figure 8: Reliability MC model for sensor H.

MTTF$_2$=3,000 h  
$\lambda_1=3.3 \times 10^{-4}$

MTTF$_3$=45,000 h  
$\lambda_3=0.22 \times 10^{-4}$

Figure 9: Reliability MC model for sensor T.

For instance as defined in §3.2., the CPT to simulate the MC for the sensor H (resp. T) reliability described in Figure 8 (resp. Figure 9) is presented in Table 9 (resp. Table 10).

<table>
<thead>
<tr>
<th>Table 9: CPT of the node H sensor(k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H sensor(k-1)</td>
</tr>
<tr>
<td>up</td>
</tr>
<tr>
<td>down</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 10: CPT of the node T sensor(k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T sensor(k-1)</td>
</tr>
<tr>
<td>up</td>
</tr>
<tr>
<td>dgd</td>
</tr>
<tr>
<td>down</td>
</tr>
</tbody>
</table>

4.3 Results and comments

Based on the incidence matrix, (see Table 6), and under any assumptions of the number of fault, then if the coherence vector issued from the residual evaluation at sample $k$ is equal to \{0 0 1\}$^T$ or to \{1 1 1\}$^T$, for example, the fault indicators I generated by a logic test is as follows:

<table>
<thead>
<tr>
<th>Table 11: Fault indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
</tr>
<tr>
<td>{0 0 1}$^T$</td>
</tr>
<tr>
<td>{1 1 1}$^T$</td>
</tr>
</tbody>
</table>

Due to the fact, the H and T fault signatures are different, and the Qo fault signature is included in the H fault signature, the fault isolation is not easily to perform. To summarise the decision and maintenance action, when the coherence vector is equal to \{0 0 1\}$^T$, the sensor Qo is down then a maintenance action is performed to repair this sensor. If the coherence vector is equal to \{1 1 1\}$^T$, the three sensors are suspected to be down with the same possibility. However, based on our approach, it could be possible to optimize the maintenance action.

In order to illustrate the performance and also the limitation of the proposed method, various faults scenari have been considered as illustrated in Figure 10:

- **Scenario A** A false alarm occurs at sample $k=700h$ which appears as an outlier on the first symptom who switched to “1” during one sample.
- **Scenario B** A failure on the sensor Qo is occurred. According to the structured residuals defined in the incidence matrix (see Table 6), only the third symptom switched to “1”. Few samples after the third symptom switched to “0” due to a maintenance action which corresponds to use a novel sensor.
- **Scenario C** During this period, no fault occurs. The system is in a fault-free case.
- **Scenario D** T and H sensors faults are supposed to occur simultaneously. Based on their fault signatures, all symptoms switched simultaneously to “1”.

The failure probabilities for the three sensors are presented in Figure 11 without taking into account the dynamic reliability of components. Otherwise, Figure 12 is devoted to the method illustration through the evolution of the failure probabilities including the dynamic reliability of components.

**Scenario A** The outlier generates a false alarms, the CPT for T can only reduced the value of failure probability (see Figure 11). However, in Figure 12, the reliability of components is similar as a sliding window and therefore annihilates the false alarm.

**Scenario B** The two BN methods isolate the fault. It could be noted that a time delay is observed for the second one due to reliability consideration.

**Scenario C** When a maintenance action is taken, the decision making is back to a fault free case.

**Scenario D** This scenario highlights the proposed approach. Without reliability consideration, it is not possible to generate a suitable decision making. For multiple faults, all fault signatures can be suspected: the
symptom u3 is explained by the failure on sensor H, then the Qo failure probability is set to "0.5156" based on the Baye’s theorem (see Figure 11). However, according to the DBN, then the Qo failure probability increases by taking into account the reliability of components (Figure 12). With the proposed method, it is possible to plan a maintenance action without visiting the Q sensor at the first place due the low level of failure probability. Then, the maintenance action can be focused to the others, T and H sensors, showing a higher level of failure probability.

Figure 11: Failure probabilities for the three sensors with BN.

Figure 12: Failure probabilities for the three sensors with DBN.

5. CONCLUSION

This paper presents a new strategy to increase the performance of the decision making in model-based fault diagnosis. The developed approach consists in taking into account in FDI scheme a priori knowledge on the system functioning and malfunctioning by a Markov chains modelling. Therefore, for complex systems, the problem of the decision making when various fault signatures vectors are identical or closed can be alleviated by using a suitable dynamic Bayesian network. The simulation example, a heating water process, has highlighted the performances of the method but also the limitations: the design of the DBN requires the false alarms and miss-detection probabilities of the residual evaluation methods which are not always possible to assess. Nevertheless, the results, obtained in this paper, are encouraging and allow us to advocate our method in order to optimize the maintenance actions. Therefore, for a system which is liable to various faults simultaneously or which is defined through an incidence matrix with similar fault signatures, the failure probabilities, provided by our method, will enable to plan the maintenance actions.

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