CHARACTERIZATION OF THE CANONICAL COMPONENTS OF A STRUCTURAL GRAPH FOR FAULT DETECTION IN LARGE SCALE INDUSTRIAL PLANTS.

P. DECLERCK, M. STAROSWIECKI
Centre d'Automatique de Lille
Université des Sciences et Techniques de Lille Flandres Artois
59655 VILLENEUVE D'ASCQ, FRANCE
Fax : 20.43.43.35
Members of WG Diagnostic, GRECO Automatique,
Pôle Automatisation Intégrée

Abstract : Fault detection in large scale physical system is more and more necessary for technical and economical reasons. Indeed, its aim is the improvement of the reliability and of the availability of the system.

The basic principle of fault detection is the comparison of the actual behaviour of the system with the nominal one describing the normal operation. Some approaches have been developped which commonly use the state and measurement equations .

However, such a representation is not often available for large scale complex industrial systems. Those systems are characterized by the great number of variables which are necessary for their description, and by the difficulty of their modelization. As a consequence, a great variety of relations linking the variables may be encountered : qualitative or quantitative, statical or dynamical, linear or non linear.

The paper presents an approach based on structural analysis in order to exhibit coherence models for fault detection in large scale systems. The initial knowledge upon the normal operation of the system is given by its representation under the form of a network of elementary activities. This network defines the structure of the system under the form of a bipartite graph linking each activity to the physical variables which are constrained by it. We propose an embedding procedure which allows to exhibit the structural overdetermination (if any) and thus the structural analytical redundancy relationships.

Keywords : Structural Analysis,Structural Solvability, Fault Detection and Isolation, Embedding Procedure, Large Scale Systems.

1. INTRODUCTION

The basic principle of fault detection is the comparison of the actual behaviour of the system to a reference behaviour describing its normal operation. The reference behaviour is issued from the knowledge which is available upon the system, this knowledge being expressed under more or less precise terms and under formalisms which may be very different (knowledge base, analytical models,...).

However, most model based failure detection and isolation methods rest on an analytical expression of the knowledge we have about the system, state and measurement equations often assumed to be linear [11].

One of the most frequently used approach is based on Analytical Redundancy : the knowledge available upon the system leads to express its normal operation by a set of invariants named residuals. The fault detection resumes thus to a decision problem : is the variance of the residuals the effect of noise, of normal deviations and errors or the effect of a failure.

The residuals are generated using state estimation [3] [10], identification [12] or direct analytical redundancy relationships (ARR) [2]. Some equivalence property between ARR and the observer based approach has been prooved (dead beat observer [9] [4] [16]).

However, it is the most frequent case that such an analytical representation is not directly available for large scale complex industrial systems. Those systems are characterized by the great number of variables which are necessary for their description, and by the great variety of the types of relationships which link these variables : qualitative or quantitative, statical or dynamical, linear or non linear.
Moreover, in practical situations, some models are not known precisely (class of the model, values of its parameters,...) although their structure, i.e the different relationships and the variables which intervene, is known. The system may thus be represented by a network of elementary activities, each of them processing a subset of variables. Among the set of all the variables, only some of them are known (computed by elementary activities) or measured (a sensor performs also an elementary activity).

The idea of the present work is to use such a representation in order to identify possible ARR for fault detection, based on the overdetermination, within the system of one or more variables [14].

The interests in developping approaches which rest on the structural model of a system are the following :

- the system's representation is close to the operators mental representation because it takes into account the topological structure of the process, and allows the identification of each hardware component of the system,

- this representation allows to take into account different levels of knowledge for the behaviour description of different system's components,

- the obtained results are, by construction, robust with respect to unknown inputs unknown system parameters, behavioural modification of the system's components, [17].

- the structural representation is well suited for direct extensions of FDI studies concerning, for instance, the need and the location of extra sensors.

The ARR are the result of a systematic approach which can be decomposed into two steps :

- qualitative step : The structural analysis of the process gives subsets of non independant known or measured variables. It gives also subsets of elementary (or process functions) which link these variables. Each of those subsets will give rise to one or more ARR,

- quantitative step : This step consists in the computation of the ARR corresponding to each of the previously mentionned susbsets.

The present work is concerned with the qualitative step. It is based on the models presented in [14] and uses an embedding procedure in order to exhibit the canonical overdetermined component of the structure of the complex system under investigation, and the associated ARR to be used in the FDI system.

The first part presents the structural representation of a complex system. In the second part, the embedding procedure is applied for the structural analysis of the system. The graph theory is used for the identification of the canonical components via a coupling approach. The third part discusses the application of structural analysis to the design of FDI procedures.

2. STRUCTURAL REPRESENTION OF COMPLEX MODEL

2.1. Structural model

The large scale system under consideration is represented by a network of elementary activities. These activities represent :

- physical constraints : Their model is derived from mass or energy balance considerations,

- control constraints : Their model is given by the control algorithms which are implemented or by the human operators who act on the system.

- measurement constraints : Their model is given by the knowledge of the sensors which are implemented on the system.

To each of the elementary activities corresponds a set of constraints possibly of different kinds which constitute the model of the activity. The overall systems is thus represented by a set of m constraints.
$F = \{f_1, f_2, ..., f_m\}$

which are applied to a set of n variables

$Y = \{y_1, y_2, ..., y_n\}$

We write :

(1) $F(Y) = 0$

We point out that no hypothesis is made about the properties of completeness of the model [13], so that m and n can take any values.
Example : A variable x is represented by x(t) in the temporal domain and by x(P) in the symbolic field.

f1 : $c_1(t) - x_1(t) + x_3(t) = 0$

f2 : $x_2(t) - x_3(t) + x_1(t) = 0$

f3 : $x_2(t) - c_4(t) = 0$

f4 : $2.x_2(t) + x_1(t) + c_3(t) = 0$

f5 : $x_2(P) + \frac{x_1(P)}{1 + \tau P} - c_2(P) = 0$

f6 : $\frac{1 + \tau_1.P}{1 + \tau_2.P} x_1(P) - x_3(P) = 0$

f7 : $a\, x_2(t) + b - x_4(t) = 0$

f8 : $x_5(t) - (x_6(t))^{1/2} = 0$

f9 : $x_6(t) - x_3(t) + x_5(t) = 0$

f10 : $-x_8(t) + x_7(t) - x_{10}(t) - x_5(t) = 0$

f11 : $-x_9(t) + (x_8(t).x_6(t))^2 + c_5(t) = 0$

The structure of the system (1) is defined by the following binary relation .

(2) $\begin{cases} S : F \times Y \rightarrow \{0, 1\} \\ (f_i, y_j) \rightarrow S(f_i, y_j) \end{cases}$

such that $S(f_i, y_j) = 1$ iff the constraint f_i applies to the variables y_j.

The exact nature of the constraints f_i and of the values of the parameters which could intervene does not matter in the structural approach if the hypothesis H holds :
Hypothesis H :
$(\forall f_i \in F) (\forall y_j \in Y) (\forall y_r \in Y)$ such that $s(f_i, y_j) = 1$ and $s(f_i, y_r) = 1$.

If the variables of $Y \setminus \{y_j, y_r\}$ are constant, a variation of y_j produces an instantaneous or in time variation of y_r.
Under this hypothesis, statical or dynamical systems can be approached with a purely boolean model For example, for the differential equation (3).

$a_1 y_1 + a_2 y_1^{(1)} + ... + a_N y_1^{(N)} = b_1 y_2 + b_2 y_2^{(1)} + ..+ b_M y_2^{(M)}$

Only, the variables y_1 and y_2 are introduced in the structure.
The bipartite graph $B_0 = G(F, Y; A_0)$ associated to the function S is defined by :

$(f_i, x_j) \in A_0 \Leftrightarrow S(f_i, x_j) = 1$

Let $\underline{P}(E)$ be the set of the subsets of a given set E

We define the following application, with $V_0 = F \cup Y$

$$\mu_A : \underline{P}(V_0) \rightarrow \underline{P}(A_0)$$
$$V \rightarrow \mu_A(V, B_0) = \{a \in A_0 \mid (\exists (v, w) \in V \times V_0) \text{ and } a = (v, w) \text{ or } a = (w, v)\}$$

$\mu_A(V, B_0)$ is thus the set of B_0's arcs such that one of their vertices belongs to V.

The application μ_V is defined by :

$$\mu_V : \underline{P}(A_0) \rightarrow \underline{P}(V_0)$$
$$A \rightarrow \mu_V(A, B_0) = \{v \in V_0 \mid (\exists a \in A) (\exists w \in V_0)\, a = (v, w) \text{ or } a = (w, v)\}$$

$\mu_V(A, B_0)$ is the set of B0's vertices which are extremities of the arcs of A .

Let {C, X} be a bi-partition of the set Y (in the application, C will be the subset of known variables and X the subset of the unknown ones).

A restriction of B_0 is defined by $B_X = G(F_X, X; A_X)$ with $F_X = \mu_V(\mu_A(X, B_0), B_0) \setminus X$

$A_X = \mu_A(X, B_0)$

3. CANONICAL REPRESENTATION

The over, under, and just determined susbsystems are now structurally characterized. Their properties lead to algorithms for the decomposition of the overall system into three parts.

3.1. Canonical representation of a bipartite graph

the following notations and definitions are described in detail in [6].

Projection : Let $E \subset F_X \cup X$. The projection over E is a function P_E defined by :

$P_E : P(A_X) \rightarrow F_X \cup X$
$A \rightarrow P_E(A) = \mu_V(A, B_X) \cap E$

Disjoint subgraph :

A graph $G^D = G(F_X, X ; A)$ is a disjoint subgraph of B_X iff considering two distinct arcs (f_i, x_j) (f_k, x_l) of A_X, $f_i \neq f_k$ and $x_j \neq x_l$. A disjoint subgraph G^D is maximal over B_X if $|A|$ is maximal. It is said complete if all the vertices of $F_X \cup X$ are covered.
The set of the maximal disjoint subgraphs of B_X will be noted $E(B_X)$.

Exterior minimal cover : A pair (α, β) is an exterior cover of B_X iff :
1) $\alpha \subset F_X$; $\beta \subset X$

2) $A_X \cap (\overline{\alpha} . \overline{\beta}) = \varnothing$

where $\overline{\alpha}$ (resp $\overline{\beta}$) is the complement of α in F (resp of β in X).
In other words , every arc (f_i, x_j) of A_X is such that either $f_i \in \alpha$ or $x_j \in \beta$.
An exterior cover (α, β) which achieves the minimal value of $|\alpha| + |\beta|$ is called a minimal exterior cover (MEC).

Définitions : A subgraph of B_X is said to be semi-irreducible iff it has a unique MEC $(\alpha, \varnothing)$ or $(\varnothing, \beta)$.
A subgraph of B_X is said irreducible iff it has two unique MEC $(\alpha, \varnothing)$ and $(\varnothing, \beta)$.
A subgraph of B_X neither semi-irreducible, nor irreducible is said reducible.

Dulmage and Mendelsohn [7] [8] define the canonical decomposition of B_X via the construction of a given number of subsets S_i and T_i (i = 1,...k) such that :

$$F_X = \alpha_* \cup S_1 \cup S_2 ... \cup S_k \cup \overline{\alpha^*}$$

$$X = \overline{\beta^*} \cup T_1 \cup T_2 ... \cup T_k \cup \beta_*$$

with :

$S_i \cap \alpha_* = \varnothing$ for i = 1, 2, ..., k
$S_i \cap S_j = \varnothing$ for all i, j, i ≠ j
$T_i \cap \beta_* = \varnothing$ for i = 1, 2, ..., k
$T_i \cap T_j = \varnothing$ for all i, j, i ≠ j
$|S_i| = |T_i|$

(α_i, β_i) is a minimal exterior cover of B_X, i = 1, 2, ...k
where $\alpha_i = \alpha_* \cup S_1 \cup S_2 ... \cup S_i$
$\beta_i = T_{i+1} \cup T_{i+2} ... \cup T_k \cup \beta_*$

If (α_*, β^*) and (α^*, β_*) are the EMEC of digraph B_X [5], the three canonical components are defined by :

$B^> = G(\overline{\alpha^*}, \beta_* \; A_X^>)$

$B^< = G(\alpha_*, \overline{\beta^*} \; A_X^<)$

$B^= = G(\alpha^* \backslash \alpha_*, \beta^* \backslash \beta_* ; A_X^=)$
with

$A_X^> = A_X \cap (\overline{\alpha^*} . \beta_*)$

$A_X^< = A_X \cap (\alpha_* . \overline{\beta^*})$

$A_X^= = A_X \cap (\alpha^* \backslash \alpha_* . \beta^* \backslash \beta_*)$

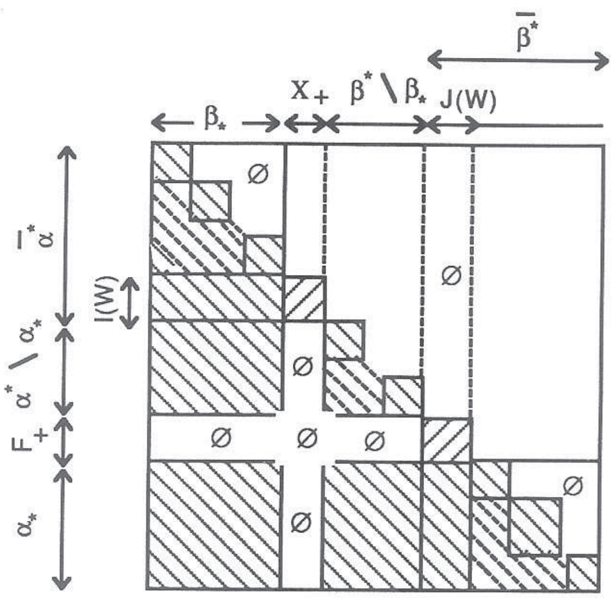

Figure 1 : the Bipartite Graph B^+

3.2. The Embedding Procedure

In this part, we define extended graphs B^+ and W^+ which include the initial structures B_X and $W \in E(B_X)$. The new structures consider all the information contained in the initial ones.

The following sets are associated to W :
$I(W) = F_X \backslash P_{F_X}(A(W))$
$J(W) = X \backslash P_X(A(W))$

The elements of I(W) (resp.J(W)) belong to F_X (rep. X) and are not the extremity of any arc of A(W) (A(W) is the set of arcs associated to W)

Let $F_+ = \{f_{i+} \mid x_i \in J(W)\}$
$F^+ = F_X \cup F_+$
$X_+ = \{x_{i+} \mid f_i \in I(W)\}$
$X^+ = X \cup X_+$
$V_> = \{(f_i, x_{i+}) \mid f_i \in I(W) \; x_{i+} \in X_+\}$
$V_< = \{(f_{i+}, x_i) \mid x_i \in J(W) \; f_{i+} \in F_+\}$

Example : $A(W) = \{(f_4,x_1), (f_5,x_2), (f_6,x_3), (f_7,x_4), (f_8,x_5), (f_9,x_6), (f_{10},x_7), (f_{11},x_8)\}$

$I(W)=\{f_1,f_2,f_3\}$ $J(W)=\{x_9,x_{10}\}$

$X+=\{x_1+,x_2+,x_3+\}$

$V>=\{(f_1,x_1+),(f_2,x_2+),(f_3,x_3+)\}$

$F+=\{f_9+,f_{10}+\}$

$V<=\{(f_9+,x_9),(f_{10}+,x_{10})\}$

Let $B^+ = G(F^+, X^+ ; A^+)$ with $A^+ = A_X \cup V_> \cup V_<$
and $W^+ = G(F^+, X^+ ; A(W^+))$ with $A(W^+) = A(W) \cup V_> \cup V_<$

The proofs of all the following properties can be found in [6].

Property 1 : The graph W^+ is a complete disjoint subgraph of B^+.

3.2.1. Preserved characteristics

The following properties show the conservation of the structure of $B^=$ in the new structure obtained by the embedding procedure. Particularly, the partition of $F_X \setminus (\alpha_* \cup \overline{\alpha^*})$ and $X \setminus (\overline{\beta^*} \cup \beta_*)$ is conserved.

Property 2 : Let $\alpha_i' = \alpha_i \cup F_+$; $\beta_i' = \beta_i \cup X_+$ (α_i', β_i') is a MEC of B^+.

Property 3 :The irreducible components B_i of B_X are irreducible in B^+.

3.2.2. New characteristics

The differences between the graphs W and W^+, B_x and B^+ are now shown.

Property 4 : The graph B^+ has no semi-irreducible components.

Let $\quad B^{>+} = G(\overline{\alpha^*}, \beta_* \cup \underline{X_+} ; A_x^{>+})$

$\quad B^{<+} = G(\alpha_* \cup \underline{F_+}, \overline{\beta^*} ; A_x^{<+})$

with $\quad A_x^{>+} = A^+ \cap (\overline{\alpha^*} . (\beta_* \cup X_+)$

$\quad A_x^{<+} = A^+ \cap ((\alpha_* \cup F_+) . \overline{\beta^*})$

The element of F_+ and X_+ are given by the knowledge of I (W) and J (W) whereas the elements of α_*, $\overline{\alpha^*}$, β_* and $\overline{\beta^*}$ are given by the following theorem based on alterned chain.

Définition : Let $W = G(F_X, X ; A(W)) \in E(B_X)$

An alterned chain $L = G(F_L, X_L ; A_L)$ on W^+ is defined by :

1) $F_L \cup X_L = \mu_V(A_L)$; $F_L \subset F^+$; $X_L \subset X^+$; $A_L \subset A^+$

2) The n arcs of A_L are renamed upon the form a_i such that :

$(\forall i = 1..n)\ (a_i \in A_L)$
$a_i \in A(W^+), a_{i+1} \notin A(W^+) \Leftrightarrow P_{F^+}(a_i) = P_{F^+}(a_{i+1})$
$a_i \notin A(W^+), a_{i+1} \in A(W^+) \Leftrightarrow P_{X^+}(a_i) = P_{X^+}(a_{i+1})$

Theorem

a) $e \in \overline{\alpha^*} \cup \beta_* \Leftrightarrow \exists L = G(F_L, X_L ; A_L)$ such that:
1) $e \in \mu_V(a_n, B^+)$

2) $P_X^+(a_1) \in X_+$

b) $e \in \alpha_* \cup \overline{\beta^*} \Leftrightarrow \exists L = G(F_L, X_L ; A_L)$ such that:
1) $e \in \mu_V(a_1, B^+)$

2) $P_F^+(a_n) \in F_+$

The proof is given in [6].

Example : $a_1=(f_1,x_1+)$; $FL=\{f_1,f_6\}$; $XL=\{x_1+,x_3,x_1\}$
$AL=\{(f_1,x_1+),(f_1,x_3),(f_6,x_3),(f_6,x_1)\}$

So, $\overline{\alpha^*}=\{f_1,f_2,f_3,f_4,f_5,f_6\}$; $\beta_*=\{x_1,x_2,x_3\}$

$\alpha_* =\{f_{10},f_{11}\}$; $\overline{\beta^*}=\{x_7,x_8,x_9,x_{10}\}$

$\alpha^* \setminus \alpha_*=\{f_7,f_8,f_9\}$; $\beta^* \setminus \beta_* =\{x_4,x_5,x_6\}$

The following properties give important indications on the structure of $B^{>+}$ and $B^{<+}$ and then on the structures of the ARR.

Property 5 : The maximal disjoint subgraph over $B^{>+}$ and $B^{<+}$are complete.

Property 6 : $(\forall W \in E(B_X))$ $B^{>+}$ and $B^{<+}$ are not irreducible.

Let us now exploit the presented properties. As W^+ is complete, the canonical decomposition applied to B^+ leads to a structure without semi-irreducible component. The structure of the irreducible components of B_X are conserved. Moreover, $B^{>+}$ and $B^{<+}$ are complete and are composed of at least two irreducible components (property 6).

We will now use the preceding results in order to exhibit all the structures of possible ARR and give a guide for the computation of the residuals.

4. APPLICATION

Let us use a special case of overdetermination is used : the overdetermination is represented by two different means for the determination of special variables.

4.1. Determination over B^+

The disjoint maximal subgraphs over B^+ are complete and so, a blocktriangularisation whose blocks are square can represent B^+ after permutation of rows and columns in a matricial formalism : all the variables can be structurally expressed (fig. 1). Identically, the maximal disjoint subgraphs over $B^{>+}$ and $B^{<+}$ are complete and a blocktriangularisation permits the expression of the variables belonging to $\beta_* \cup X_+$ and $\overline{\beta^*}$.

4.2. Redundancy

The process, described by B_0 or B_X is a physical one and so, each variable which belongs to Y or X obviously exists. Under the hypothesis that the model represents perfectly the process and that the sensors introduce no noise, the system of equations is compatible. The graphs B_0 and B_X are the structural representations of a compatible system of equations.

An other description is given by the graph B^+ which includes the initial structure of B_X. This superstructure is distinguished by the introduction of the variables $x_{i+} \in X_+$ and relations $f_{i+} \in F_+$ whose roles will now be precised.

Roles : - F_+ : For every variable of J(W), a function f_{i+}, which constitutes a new constraint, has been introduced. In order to achieve the equivalence of the models represented by B_X and B^+, each f_{i+} is given by the following form :

$f_{i+} : x_i = I_i$
with $x_i \in J(W)$
$I_i \in]-\infty, +\infty[$
The introduced variable I_i is unknown (case a).

- X_+: For every function of I(W), a variable x_{i+} which constitutes a new degree of freedrom, has been introduced. In order to achieve the equivalence of the models represented by B_X and B^+, each function of I(W) is given by the following form :
$f_i : f_i\,(C, X) + x_{i+} = 0$
with $x_{i+} = 0$
The introduced variable x_{i+} is known (case b).
Note that the algebraic information (a) and (b) are not introduced in the graph B^+ in order that the disjoint subgraph would be complete.
Let us now discuss the physical interpretation of the system described by B+ .
- F+ : Every function f_{i+} of F_+ represents a fictitious sensor whose measure is I_i (fig. 2). However, this data cannot reach the supervisor computer : no line exists or the sensor does not operate. So , I_i is unknown .

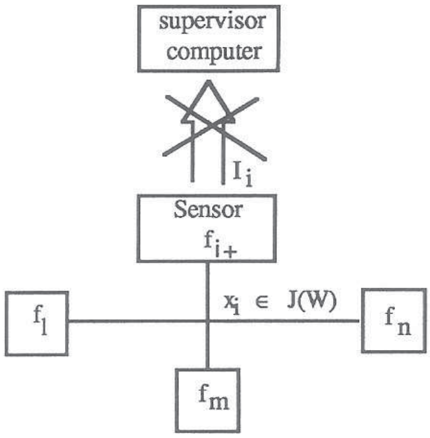

Figure 2

- X+ : Every variable x_{i+} of X+ is a fictitious ouput variable of a function f_i (fig. 3). However, this variable is a data already known whose value has to be zero. The detection procedure will compare to zero the actual ouput variable (a residual)

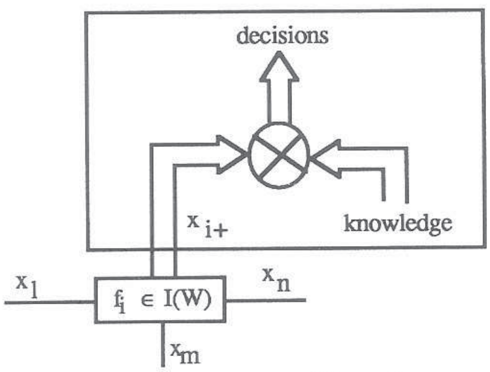

Figure 3

Exploitation : two kinds of information concern the variables of X+ :
- algebraic information
$(\forall\ x_{i+} \in X_+)\ \ x_{i+} = 0$
- structural information
$(\forall\ x_{i+} \in X_+)\ \ x_{i+} = f(C)$ where f represents the structural expression of x_{i+}, the two knowledges being different, the redundancy is concretely expressed by :
$(\forall\ x_{i+} \in X_+)\ \ f(C) = 0$
The number of ARR is equal to the cardinal of X_+.
For the FDI application, each variable x_{i+} represents a residual which can be tested by a decision procedure.
Example : The ARR are in the symbolic field :

$$x_{1+} = c_1 - c_3\left(1 + \frac{2}{2 + \tau P}\right) + c_2\ 2\frac{(1 + \tau P)}{2 + \tau P} = 0$$

$$x_{2+} = -\,c_2\frac{(1 + \tau P)}{2 + \tau P} + c_3\left[1 + \frac{1}{2 + \tau P}\left(2 + \frac{1 + \tau_1 P}{1 + \tau_2 P}\right) + \frac{(1 + \tau_1 P)}{(1 + \tau_2 P)}\right]$$

$$x_{3+} = c_2\frac{(1 + \tau P)}{(2 + \tau P)} - \frac{(c_3)}{(2 + \tau P)} - c_4$$

The structure of the ARR relatively to the sensors and the physical functions can be written in a qualitative sensitivity table.

	c_1	c_2	c_3	c_4	f_1	f_2	f_3	f_4	f_5	f_6
ARR1	x	x	x		x			x	x	x
ARR2		x	x			x		x	x	x
ARR3		x	x	x			x	x	x	

(c_1,c_2,c_3,c_4 are sensors)

Each column represents the sensitivities to the corresponding element. So, the isolation of a component can be made, if the respective column is different from the others. Equally, two components which present identical columns can not be structurally isolated .
Moreover, the structural table can be used on-line : the fault of an element has for consequence, the modification of the residuals which are sensitive to it. For example, the result of the fault of the function f6 would be appearent through the test of the residuals x_{1+} and x_{2+}.

V. CONCLUSION

The design of model based FDI procedures for complex industrial plants supposes the handling of large scale models. These plants are often constituted by the interconnexion of a great number of elementary activites, each of them being represented by an elementary model, more or less precisely known. Structural analysis gives a means to identify those parts of the overall system whose instrumentation gives enough information for FDI procedure. The problem is that of the decompostion of a bipartite graph into its three canonical components, namely the under, just and overdetermined subsystems. Stárting with the initial graph, we use an embedding procedure in order to construct an overgraph on which some simple manipulations lead to the canonical decomposition. The overdetermined subsystem represents the structure of the part of the overall system which can be monitored via the FDI procedure.

References

[1] BARTNIK G.W.
Algorithmes de couplages dans les graphes
Thèse de doctorat troisième cycle.
Université Paris VI, 1978.

[2] CHOW E.Y., WILLSKY A.S.
Analytical redundancy and the design of robust failure detection systems.
IEEE Trans. on A.C., Vol. AC-29 n° 7, July 1984.

[3] CLARK R.N.
A simplified instrument failure detection scheme.
IEEE Tran. Aerospace Electron. Syst. Vol. 14, 558-563, 1978.

[4] CLARK R.N.
State estimation schemes for instrument fault detection
in Fault diagnosis in dynamic systems, theory and applications, Prentice Hall, 1989.

[5] DECLERCK P., STAROSWIECKI M.
Identification of structurally solvable subsystems for the design of Fault Detection and Isolation schemes, using the embedding procedure.
9th IFAC/IFORS Symposium on identification and system parameter estimation.
Budapest, July 8-13, 1991.

[6] DECLERCK P.
Thèse de doctorat ,Université des Sciences et Techniques de Lille Flandres Artois, Villeneuve d'ascq, to appear.

[7] DULMAGE A.L. and MENDELSOHN N.S.
Coverings of bipartite graphs.
Canad. J. Math., 10, 517-534, 1958.

[8] DULMAGE A.L. and MENDELSOHN N.S.
A structure theory of bipartite graphs of finite exterior dimension.
Trans. of Royal Soc. Canada, Section III, 53, 1-13, 1959.

[9] FRANK P.M.
Robust fault diagnosis using unknown input observer schemes.
in Fault diagnosis in dynamical systems, theory and applications, Prentice Hall, 1989.

[10] FRANK P.M.
Fault diagnosis in dynamical systems using analytical and knowledge-based redundancy. A survey and some new results.
Automatica, Vol. 26, 459-474, 1990.

[11] GERTLER Janos J.
Survey of model-based failure detection and isolation in complex plants.
IEEE. Control System Magazine, 3-11, December 1988.

[12] ISERMANN R.
Process fault detection based on modeling and estimation methods. A survey.
Automatica, Vol. 20, 387-404, 1984.

[13] STAROSWIECKI M., DECLERCK P.
Analytical redundancy in non linear interconnected systems by means of structural analysis.
IFAC Symposium on Advanced Information Processing in Automatic Control, 3-5, July 1989, Nancy.

[14] STAROSWIECKI M., CASSAR J.Ph, DECLERCK P.
Automatic Analytical Redundancy relationships in complex interconnected system based on a structural approach.
INCARF 89 New Delhi.

[15] SUEUR C.
Contribution à la modèlisation et à l'analyse des systèmes dynamiques par une approche Bond-Graph, Thèse de doctorat, 5 oct. 90, Université des Sciences et Techniques de Lille Flandres Artois .

[16] STAROSWIECKI M., COCQUEMPOT V., CASSAR J-P.
Observer based and parity space approaches for failure detection and identification .
IMACS MCTS, Lille , may 91 .

[17] COCQUEMPOT V., STAROSWIECKI M., CASSAR J.P.
Generation of robust analytical redundancy relations.
First European Control Conference, ECC'91, Grenoble, France, 2-5 july 91.