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BOND GRAPH MODEL – INTELLIGENT ONLINE DIAGNOSTICS FOR EDUCATION

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ABSTRACT

Nowadays, the control of physical systems is the result of many steps, from design to implementation, modelling and analysis, Especially in the field of education and innovation. It is often necessary to know in advance the performance of the system under study and in this case a mathematical model is more than useful. For economic and performance reasons, it is often necessary in certain situations to have a precise representation of physical phenomena, which leads to complex models and the mathematical tools are not always adapted to the models obtained. For several decades, the most exploited representation has probably been the state representation, or an extension of this form for non-linear models. For some time now, the algebraic approach has been used to discover other characteristics of the models, or at least a new interpretation of properties well known to automaticians. However, these techniques are difficult to use for the uninitiated, and the representation by a link graph model allows to reconcile all the theoretical concepts, which are necessary in the different design phases. Some analysis techniques for design are proposed by bond graph modelling for linear models, but can be quite easily generalised for more general models. In this paper, the bond graph tool proves its intelligence in the implementation of monitoring systems, and in particular an intelligent design support. The causal properties of the bond graph allow to analyse the necessary monitoring conditions before and after the design to generate diagnostic algorithms in a generic way. The following approach is illustrated on a DC motor.

Keywords: *Diagnosis, Bond graph, Intelligence, Education, Implementation.*

1. INTRODUCTION

Although industrial control and regulation are widely mastered by the industrial world, on-line monitoring is little developed. An ambiguity in its definition often reduces it to the tasks of monitoring parameters or managing alarms by thresholding variables. The improvement of the operating safety of systems is essentially based on the algorithms for detecting and isolating on-line faults, known under the English expression Fault Detection & Isolation (FDI) [1]. The bond graph tool [2], which has proven its effectiveness in building knowledge models of multidisciplinary physical systems, can also be an excellent support for the study of industrial system monitoring. It is with this objective in mind that we have been developing tools and methods for the integrated design of monitoring systems, ranging from modelling [3], the generation of robust on-line diagnostic algorithms and the means of reconfiguration in degraded modes [4].

So-called modern automatic control emerged in the 1960s thanks in particular to the work of Kalman (Kalman, 1963), who proposed a new representation, called state representation, and introduced the notions of controllability and observability. notions of controllability and observability [5-7]. His work subsequently gave rise to a multitude of research articles. Many authors have made the link between the properties of state models and models in the form of input-output representation [8-9]. The notions of poles and zeros that characterise the models have thus been widely The notions of poles and zeros that characterise models have been widely discussed and the intrinsic characteristics of state models have been highlighted [10-12] (Rosenbrock 1970, Brunovsky 1970, Morse 1973, Kailath, 1980).

Thanks to this representation, many control strategies have been developed, with more or less control strategies have been developed, with varying degrees of success, exploiting in particular state

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feedback control, with different types of specifications such as pole placement, input-output decoupling or disturbance rejection [13].

State representation makes extensive use of concepts related to vector spaces, which seems quite natural, given the matrix nature of this representation [14]. Thus, towards the end of the 1960s, the geometric approach appeared, which allowed a very intuitive formulation of control problems in terms of vector spaces (Basile and Marro, 1969, Wohnam and Morse 1970). Numerous research results are available from this approach (Wohnam 1985, Basile and Marro 1992) and even today research work is carried out using this approach.

The study of dynamical systems using the algebraic approach was proposed by M. Fliess (Fliess 1990). This new approach has made it possible to define in a more general way the notion of dynamic model as well as all the properties associated with models, which are and all the properties associated with models, such as controllability and observability. A fundamental characteristic of this approach is that some properties are independent of the variables chosen, such as the variables, such as the controllability property [6], for which a simple extension to the non-linear case is possible, in particular possible, in particular through differentially flat systems (Fliess et al 1992, 1995).

The present work presents the methodological approach for the online diagnosis of systems described by bond graph models. This systematic approach to monitoring system design is based on the causal, structural and behavioural properties of the bond graph.

After a presentation of the principle and methods of diagnosis, the third section concerns the bond graph methodology for the design of on-line diagnosis of industrial systems. The approach will be illustrated by a pedagogical application on a DC motor.

2. BOND-GRAPH APPROACH AND MODELLING

2.1 Modelling with the bond graph tool is carried out in five steps [15-16]:

- Functional analysis: the system is broken down into subsystems that exchange power, which leads to the bond word graph,
- Phenomenological analysis: depending on the modelling hypotheses and the range of validity (dynamic, frequency) sought for the model, the components and physical phenomena that dissipate or store energy are identified, and energy, mass and movement quantity balances are carried out. This leads to the detailed bond graph,
- Causal analysis: highlighting the causal relationships allows the identification of possible future problems for the simulation of the model (implicit equations, algebraic-differential), which may lead the modeller to reconsider his modelling hypotheses. The resulting model is a causal graph jump.
- Structural analysis: the application of graphical procedures (manipulation of causality, path traversal on the bond graph) enables the structural properties of the model to be highlighted (therefore valid whatever the numerical values of the parameters)
- Specification of the characteristic laws of the elements retained in the "phenomenological analysis" phase and writing of the global mathematical models associated with the bond graph model

2.2 Approach bond graph

The structural approach proposed, for example, by means of a graphical approach (Lin 1974) consists, for controllability, in verifying two properties, that of the attainability of the state variables by the controllability consists in checking two properties, that of the reachability of the state variables by the control variables (there is a "path" between one of the control variables and each of the state variables) and the study of the structural rank of the matrix [A B], concatenation of the matrices A and B. Bond graphs are also based on these techniques (Sueur and Dauphin-Tanguy 1991) [17]. The notion of rank bond graph first proposes a general framework for which the notion of causality appears as a central element. Two types of causality can be applied to a bond graph model, the first one consists in choosing preferably an integral causality for the dynamic The first is to choose an integral causality for the dynamic elements, the second a derived causality. For the first choice, the for the first choice, the bond graph model will be noted BGI, for the second BGD [18].

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Definition 1: The bond graph rank of the state matrix A, noted rank-BG(A), associated with a bond graph model is given by the difference between the number n of elements I and C in integral causality of the bond graph model BGI and the number k of dynamic elements I and C in integral causality of the bond graph model BGD.

For bond graph models, the study of the rank of the state matrix A corresponds to the determination of the number of structurally zero eigenvalues of A.

Definition 2: Dualising a source or detector consists in reversing its causality. Thus a dualized force control source *MSe* (respectively a force detector *De*) becomes a flux source $(\widetilde{MSe} \equiv MSf)$ (respectively a flux detector *Df*) and inversely.

Property 1: A bond graph model is structurally state-controllable if and only if the following two conditions are met conditions are met:

i) On the bond graph model BGI, there is a causal path between all dynamic elements I and C in (i) On the bond graph BGI model, there is a causal path between all dynamic elements I and C in integral causality and a control source *MSe* or *MSf.*

ii) All dynamic elements I and C admit derivative causality on the bond graph model BGD. If any of the if dynamic elements I or C remain in integral causality, the dualisation of control sources *MSe* or *MSf* must allow them to be put in derivative causality.

The first condition is equivalent to the attainability condition, while the second consists in the study of the rank bond graph of the matrix [A B]. When a dynamic element I or C in full causality is causally reached by an input source through several direct causal paths, the causally reached by an input source through several direct causal paths, it is necessary to verify that these paths do not (the sum of the gains is zero). When it is necessary to dualise at least one input source, the state matrix contains zero eigenvalues. Moreover, for a linear graph bond model, the non-controllable modes can only be zero.

Property 2: A bond graph model is structurally observable in state if and only if the following conditions are met:

iii) On the bond graph model BGI, there is a causal path between all dynamic elements I and C in causality and a detector *De* or *Df*,

iv) All dynamic elements I and C admit derivative causality on the bond graph model BGD. If any of the If dynamic elements I or C remain in integral causality, the dualization of detectors *De* or *Df* must allow them to be put in derivative causality. to put them in derivative causality.

A practical consequence is that if all the elements I and C admit derivative causality, only one actuator (resp. sensor) is needed for the model to be controllable (resp. observable), and this actuator (resp. sensor) can be placed anywhere. Only technological considerations need to be taken into account for the positioning of these components. If *k* dynamic elements I or C remain in full causality on the bond graph BGD model, at least *k* actuators and *k* sensors must be well placed. Causality allows the correct positioning of these components to be identified very directly and fits well into the integrated design of a control and measurement architecture through a single graphical analysis. The concept of causality is of course at the heart of this approach.

2.3 Algebraic approach

The above approaches are intimately linked to the mathematical or graphical representation chosen for the physical system. physical system. The notion of controllability is intrinsic to the modelling hypotheses retained for the system, independently of the chosen representation. system, independently of the chosen representation. An interpretation of the properties of controllability and observability is recalled in terms of mathematical relationships between model variables. This approach is the basis of the algebraic approach, which is proposed here because, unlike the state and bond graph approaches, it can be used in a way that is more efficient than the other approaches, it is used in an identical way for the case of non-linear systems.

Property 3: A linear model is controllable if and only if there are m variables ($z_1, \ldots, z_m$) such that:

any variable in the system can be written as a finite linear combination of the components of z and their derivatives.

- any component of z can be written as a finite linear combination of the system variables and their derivatives.
- the components of z are independent.

Property 4: A model $\sum$ is state observable if each variable in the model (e.g. state variables) can be written as a linear equation of the output variables (measurements), the input variables and their derivatives.

3. PRINCIPLE OF DIAGNOSIS

Figure 1 shows the stages of an on-line diagnostic system. The specification in a monitoring system is (based on the instrumentation architecture) to specify the relevant equipment to be monitored, while minimising false alarms, non-detections and delays in detection [2].

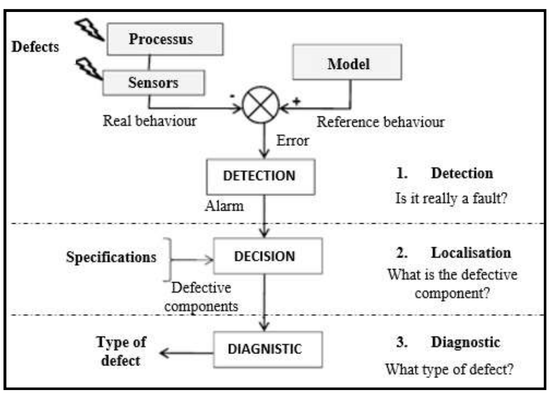

Figure 1: Stages Of A Diagnostic System.

The first step, called detection, consists in deciding between two hypotheses H0 (the system is in normal operation) and H1 (the system is in faulty operation). It is therefore obtained by testing the consistency between the real operation (provided by sensors) and what it should be under the hypothesis of normal operation: this implies that a model of normal operation is obtained by learning or analytically, and that an alarm is produced when differences are detected.

The decision procedure leads to the definition of thresholds that allow non-detection or false alarms to be accepted with a reasonable risk. The problem consists in distinguishing disturbances and uncertainties of measurement and parameters from failures.

The localisation consists of filtering the alarms to find their origin and isolate the faulty component. This is done by using listed fault signatures.

If the fault is "tolerable", the system can continue to operate. If the fault is conditionally tolerable, then the system will continue to operate, but in a degraded mode until maintenance is performed. This part is dealt with by Fault Tolerant Control (FTC) methods. A book on this approach can be found in [19]. The steps described are performed online.

Once the fault has been located, the precise causes of the fault must be identified. This is done using signatures defined by experts and validated after repairing the faults. This so-called diagnostic stage is carried out offline.

In industry, the first diagnostic methods were based on the redundancy of equipment deemed critical to the operation of the system. This approach entails a significant cost in instrumentation, is simple and easy to implement, but is limited to monitoring sensors: physical failures cannot be detected. The progress made in the field of computers now allows the implementation of modern methods of automatic control and artificial intelligence. These new approaches make it possible to eliminate some or all of the hardware redundancy for diagnosis.

Depending on the type of model used, a distinction is made between so-called analytical model-based methods and model-free methods (so-called signal-based methods or methods without a priori models). The model-free methods, which do not have operating models, use artificial intelligence learning or pattern recognition procedures which consist of automatically classifying patterns into modes (classes) known a priori. Therefore, these techniques need to know a priori all operating states (normal and faulty), which is often unacceptable in real systems.

The performance of model-based methods is highly dependent on the model used. Once the model has been generated, fault indicators can be derived from the mathematical model in both faulty and normal modes. These fault indicators are represented by Analytical Redundancy Relationships (ARR) [20].

4. BOND GRAPH METHODOLOGY FOR ONLINE MONITORING

The bond graph tool was initially used for modelling physical systems. The idea of using a single representation (the bond graph) for modelling, analysing and synthesising control laws by exploiting causality is recent. Several works have been developed in this field. Monitoring, with its aspects of detection and localisation of failures, but also the choice and placement of sensors, is also of interest in the existence of such a model.

With regard to the existing work on this theme, the contribution of the present approach is situated at several levels:

- The approach is a complete approach for the design of a supervision system: it consists in generating dynamic models (in normal and faulty mode), formal monitoring algorithms from not mathematical equations but from the physical process to be monitored. The approach is generic and flexible and uses only one representation: the bond graph.
- The algorithm for generating RRAs from the bond graph model is not only limited to particular forms of the model (polynomial for the elimination theory or linear for the projection method in the case of the parity space) but also to models given in empirical form.

4.1 Stages of diagnosis by Bond graph

- Specification and modelling

To illustrate the methodology, the diagnosis of an electric motor is considered. The schematic diagram and the bond graph model in integral causality are given (Fig. 2). The construction of the bond graph model was detailed in the first chapter. The inductor current if is assumed to be constant. Let be the parameter vector.

The performance of the system to be monitored depends mainly on the instrumentation architecture. In the case studied, this consists of the current sensors in the stator (measured by the flux sensor noted Df:im) and the angular speed sensor represented by Df:ωm. In the specifications, we propose to determine the monitoring conditions of the following components: the current and speed sensors, the electrical and mechanical parts of the motor, the load and the faults that may affect the transformation phenomena of electrical energy into mechanical energy.

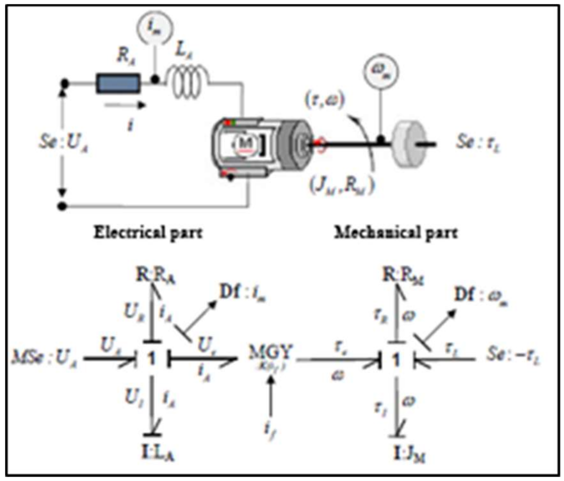

Figure 2: Electric Motor And Its Bond Graph

- *Structural surveyability*

An Analytical Redundancy Relation (ARR) is a constraint calculated from an overdetermined and observable subsystem and expressed in terms of known process variables. It has the following symbolic form:

$$F(K)=0$$

The numerical evaluation of an RRA leads to a residual r: $r = f(K) \approx 0$ whose numerical value in the absence of failures must be zero. In a bond graph representation, the relationship of an RRA becomes:

$$F(De, Df, Se, Sf, MSe, MSf, \theta) = r \approx 0$$

This residual or fault indicator expresses the inconsistency between the available information and the theoretical information provided by a model (supposed to describe the process correctly).

The initial conditions in industrial processes are usually not known, so the initial bond graph model used for diagnosis is put into derivative causality. The bond graph model of the DC motor in derivative causality is given in Figure 3.

In addition to its causal properties, the bond graph model has structural properties allowing to represent

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a system by a bipartite graph: G (C, A, Z) with two partitions: the set of constraints C (models) and the set of variables Z. A is the set of arcs defined as follows: $(c_i , z_j) \in A$ if the variable z_j appears in the constraint c_i.

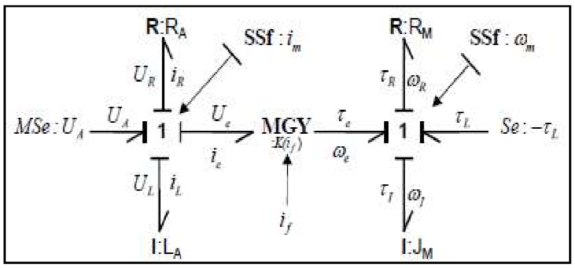

Figure 3: Diagnostic Bond Graph Model

The set of constraints C is represented by the union of structural constraints (energy conservation equation from the junctions), behavioural constraints (how energy is transformed, from the constitutive equations of the bond graph elements), measurement equations (from the detector equations).
The variables are made up of known K and unknown X. The known variables K are those of the detectors and sources and the unknown variables X are those of the power links in the C, I and R elements
The set of constraints for the motor is deduced directly from the bond graph model (fig.3):

$$\begin{cases} C_{J1A}: U_A - U_R - U_L - U_e = 0,\ i_R = i_I = i_e = i \\ C_{RA}: U_R - R_A i_R = 0 \\ C_{LA}: U_I - L_A \dfrac{d}{dt} i_L = 0 \\ C_{GY2}: \tau_e - K(i_f) i_e = 0 \\ C_{J1M}: -\tau_L - \tau_R - \tau_I + \tau_e = 0, \omega_R = \omega_L = \omega_e = \omega \\ C_{GY1}: U_e - K(i_f)\omega_e = 0 \\ C_{RM}: F_{RM}(\tau_R, \omega_R) = 0 \\ C_{JM}: \tau_I - J_M \dfrac{d}{dt}\omega_I = 0 \\ C_{m1}: i = i_m \\ C_{m2}: \omega = \omega_m \end{cases} \tag{1}$$

To which are added the derivation constraints:

$$C_{d1}: z_1 = \frac{di}{dt}$$

$$C_{d2}: z_2 = \frac{d\omega}{dt} \tag{2}$$

The unknown and known variables derived from the engine bond graph model are:

$$\begin{cases} X = \{U_R, i_R\} \cup \{U_L, i_L\} \cup \{U_e, i_e\} \cup \{\tau_e, \omega_e\}\{\tau_I, \omega_I\} \cup \{\tau_R, \omega_R\} \\ K = \{i_m, \omega_m\} \cup \{U_A, \tau_L\} \end{cases}$$

To the unknown variables are added the variables z_1 and z_2.

- *Generation of fault indicators*

The algorithm for generating the RRAs from the BG model is performed in the following steps:

1. Putting the bond graph model in derivative causality by reversing the causalities of the sensors. Thus the sensors become sources of information noted *SSf* or *SSe* (source of signal).

2. Write the 0 and 1 junction structure equation (representing power conservation) containing at least one sensor:

$$\sum_{i=1}^{n} e_i = 0, \quad \text{or} \quad \sum_{i=1}^{n} f_i = 0,$$

- Eliminate the unknown variables (e_i or f_i) by traversing the causal paths on the bond graph from the unknown variable to a known variable (sensor or source),
- for any detector whose causality is reversed, an RRA is deduced,
- for any detector whose causality cannot be reversed an RRA is deduced by equating its output with the output of another detector of the same nature (material redundancy) located in the same junction.

The signature of the residual is then easily deduced: indeed, the RRA is sensitive to the defects associated with the parameters and sensors contained in its expression and to the physical defect related to the conservation equation. An RRA deduced for example from the conservation equation of mass or energy will be sensitive to a leakage of matter or energy. Moreover, the parameters have a more explicit physical meaning than the equations deduced by the first principle or state.

The structure equation from junction 1 of the electrical part (fig.3) is:

$$C_{J1A} : U_A - U_R - U_L - U_e = 0$$

The variables U_A, U_R, U_L and U_e are unknown. They will be eliminated on the graph by a causal path from the unknown variable to a known variable (sensor or energy source) as follows:

$$\begin{cases} U_A \to MSe \\ U_R \to C_{RA} \to i_R \to C_{m1} \to SSf : i_m \\ U_L \to C_{LA} \to z_1 \to C_{d1} \to i_L \to C_{m1} \to SSf : i_m \\ U_e \to C_{GY1} \to \omega_e \to C_{m2} \to SSf : \omega_m \end{cases} \quad (3)$$

3. The first RRA is then generated by replacing the unknown variables in the junction equation with their expressions:

$$RRA1 = MS_e - R_A i_m - L_A \frac{di_m}{dt} - K\omega_m \quad (4)$$

4. We move on to the next junction.

$$C_{J1M} : -\tau_R - \tau_J + \tau_e + \tau_L = 0 \quad (5)$$

The same procedure leads to the following RRA:

$$RRA2 = -Se - F_{RM}(\omega_m, R_M)^{-1} - J_M \frac{d\omega_m}{dt} + Ki_m \quad (6)$$

5. If the second RRA is independent (different signature) from the first, then it is kept, otherwise it is rejected. The reader can for example check that the RRAs deduced from the conservation equations of the Gyrator are dependent on those obtained from the 1-junctions.

Finally, repeat step 4 until the set of independent RRAs is obtained. This process of eliminating the unknown variables results in a directed graph showing the order of the RRA calculation (Fig. 4).

4.2 Decision

- *Fault Signature Matrix*

The structure of the RRAs forms a binary Fault Signature Matrix (FSM) S_{ji} which tells us about the sensitivity of the residuals (R_i) to failures of the physical process components (sensors, actuators, controllers, physical elements). The elements of the matrix are defined as follows:

$$Sji = \begin{cases} 1, & \text{if } Ri \text{ is sensitive to the } j \text{ defect} \\ 0, & \text{otherwise} \end{cases}$$

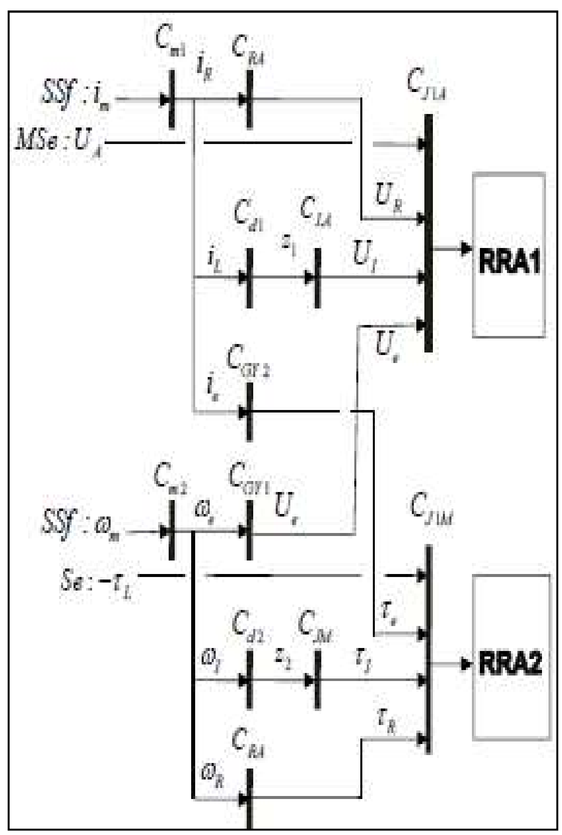

Figure 4: Oriented Graph From The Bond Graph

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The FSM provides the logic for locating faults detected during system operation. Table 1: (a) shows the MSF of the engine. Each component has a signature represented by a row vector of the matrix. A failure affecting it is locatable if and only if its signature is unique, i.e. different from the signatures of the other components.

The objective of the localisation procedure is to provide the operator with the list of failed components (chosen according to the specifications). Mb (Monitorability) and Ib (Isolability) represent respectively the Boolean indices of detectability and isolability. It can be seen that all faults that can affect the components are detectable but none are isolable.

Table 1: MSF of the Engine (a)

Ri/faults	Mb	Ib	R1	R2
Mse	1	0	1	0
i_m	1	0	1	1
ω_m	1	0	1	1
GY	1	0	1	1
Elec.	1	0	1	0
Mecha.	1	0	0	1
Load	1	0	0	1

(a)

Table 2: Redundant sensor (b)

Ri/faults	M_b	I_b	R1	R2	R3
Mse	1	0	1	0	0
i_m	1	0	1	1	0
ω_m	1	**1**	1	1	1
GY	1	0	1	1	0
Elec.	1	0	1	0	0
Mecha.	1	0	0	1	0
Load	1	0	0	1	0
ω_{m1}	1	**1**	0	0	1

(b)

- *Placement of sensors*

The monitorability of an industrial system depends on the number and placement of sensors. Thanks to its graphical architecture, the bond graph model allows an explicit placement of sensors. One can either propose a combinatorial sensor placement as developed in [19] or in a "manual" graphical way directly on the bond graph (see Fig.5). As an example, an addition of a redundant sensor ω_{m2} to the one placed in the mechanical part ω_{m1} allows to improve the monitorability of the global system as shown in the MSF of Table 2 (b). The redundant sensor cannot be dualized without introducing a causality conflict on junction 1. A RRA hardware R3 is then derived.

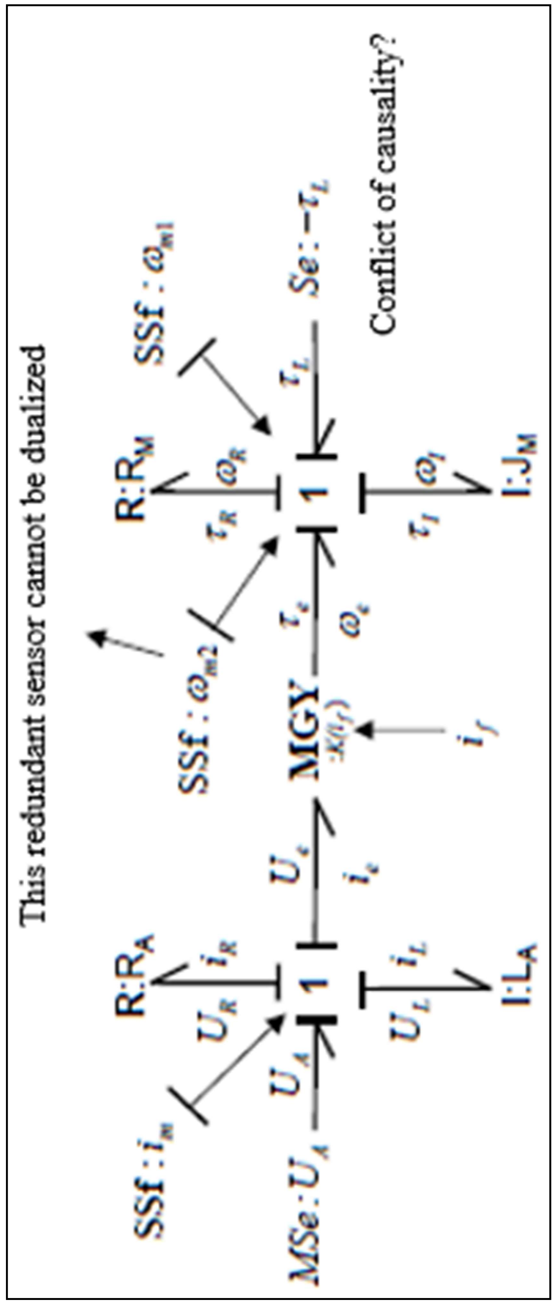

Figure 5: Bond Graph After Adding A Sensor

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4.3 Implementation and Automation of Procedures

- Design levels

The design of a diagnostic system can be carried out in two levels as shown in Figure 6. The first level is carried out off-line before design and allows the best instrumentation architecture to be determined to meet the specifications from the Detailed Instrument Plan (DIP) of the system. Once the best sensor placement (ensuring structural monitorability according to the specifications) is determined, the monitoring system is implemented in real time. The operator will then be able to check whether the MSF determined before design corresponds to the real one.

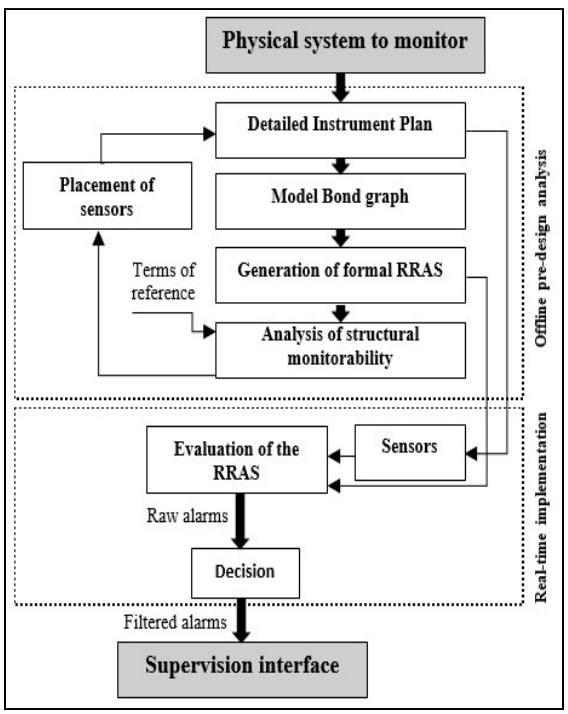


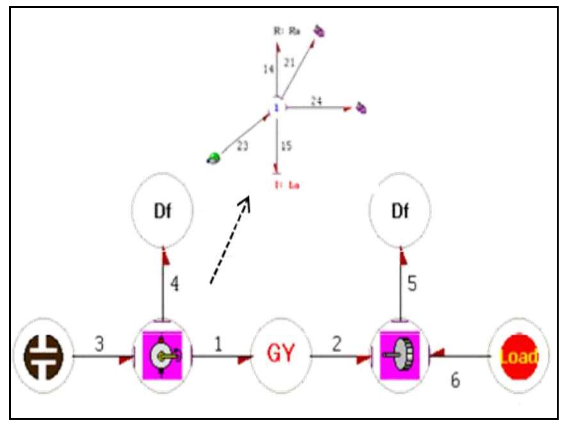
Figure 6: Design Of The Diagnostic System

- *Procedure Automation*

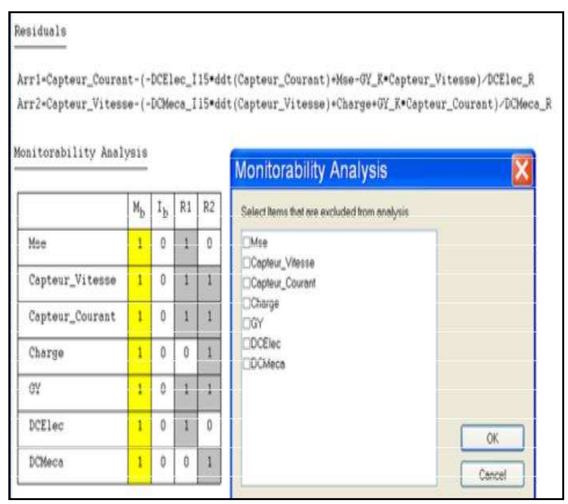
The first level procedures can be automated using an FDIpad toolkit developed in the Symbols2000 software [21]. The application results on the engine obtained manually above are automated in the following steps:

- Generic models encapsulated in a business icon (recognisable by the industrialist) are created and then connected to form the global architectural model of the engine (see Fig. 7a).
- The generation of the dynamic model, the fault indicators, the specifications and the MSF are generated through a user-friendly interface and an appropriate menu.

Finally, a sensor placement is proposed graphically by the operator on the software to generate the new MSF (Fig.8a and Fig.8b) and satisfy the specifications.



(a)



(b)

Figure 7: Use Of Dedicated Fdipad Software

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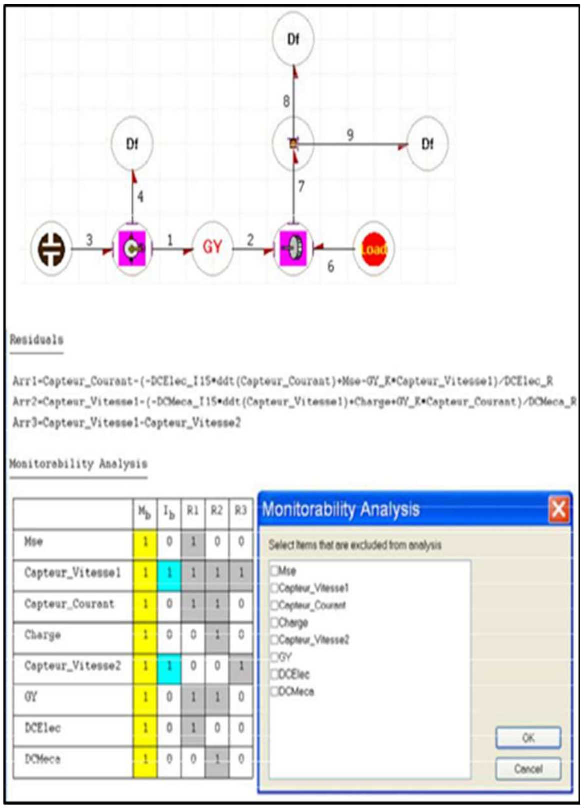

Figure 8: Automation Of Sensor Placement

5. CONCLUSION

The study of a control and measurement architecture is an integral part of integrated system design. Different techniques can be used, depending on the nature of the models chosen. We have proposed a bond graph approach, based on theoretical concepts related to state models. This bond graph approach is purely graphical. It allows feedback on the model but also to choose the most appropriate control and measurement architecture for a given objective.

The realisation of a model-based monitoring system is a costly operation requiring several complex steps. The bond graph tool by its causal and structural properties thanks to its graphical aspect, and behavioural by its functional architecture is well adapted for the design of such systems. Finally, the generic aspects of this tool have enabled the implementation of a software tool for the automation of procedures, thus reducing the cost of designing monitoring systems. We will adopt this technology in the future in scientific projects in the field of education in general, and the field of technology and denial in particular.

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