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FDI OF SMART ACTUATORS USING BOND GRAPHS AND EXTERNAL MODELS

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Abstract: In the paper, we interest to smart actuators. External model has been defined in order to improve behavioural of actuator in presence of failures. The external model requires information from Fault Detection and Isolation algorithms. To complete the information providing to the users, we associate bond graph methodology to the external model in order to complete the information with physical knowledge. The objectives are to obtain self-diagnosis intelligent actuators. In the final paper, the proposed description will be applied to an intelligent actuator which integrates a control valve, a pneumatic servomotor and a positioner. Copyright ©2002 IFAC.

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1. INTRODUCTION

[1] Smart actuators participate to the information system of the automated process. Their local processing power allows the processed information to be more numerous, and increases the possibilities of the global system. In addition to control possibilities, they create a great number of data which can be communicated to the various operators which intervene all along its life cycle. The smart actuators are in general integrated within a global system with higher level production goals. The correct achievement of these goals is obtained as long as the actuator is able to process correctly the operating requests which are communicated to it by the higher levels. The introduction of Fault Detection and Isolation (FDI) techniques may bring down the periodical inspection costs.

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Many works have been carried out to provide functional, behavioural, object-based, internal or external models of smart equipment (Staroswiecki and Bayart, 1996). The external model, using the concept of service offered to users and an organization based on operating modes, has led to a generic model description that allows to specify and to qualify smart instruments and hybrid systems.

The drawback of external model as described in the cited references is that it consists of describing the system in terms of functions without taking into account its physical and dynamic behaviour. This is why, the Bond Graph methodology as graphical modelling language becomes a convenient and useful tool for those purposes. Furthermore, the causal properties of Bond Graph methodology are helpful for FDI design. In this way, by adding a bond graph methodology, it becomes possible to obtain physical knowledge of the actuators, and to improve their monitoring, and consequently to insure a best safety.

After a bried description of bond graph tool, the external model concepts in the bond graph sense are presented in the first section. The second part of the paper presents FDI of smart actuator using bond graphs. The final section presents the application of the proposal methodologyl to a smart actuator.

2. EXTERNAL MODEL IN A BOND GRAPH SENSE

Bond graph modelling is based on considering the power exchange between the elements of a system. Bond graphs display both energy and signal exchanges between components by simple lines and symbols. Since bond graph theory has been presented extensively in the literature, (Karnopp et al., 1990), (Thoma and Ould Bouamama, 2000), in this paper we will essentially deal with those aspects of bond graphs in the sense of component model. and the use of bond graph tool for smart actuator monitoring.

From an external point of view, an automation system provides services to users. Users request services for a specific purpose. At each time, the smart actuator as a system carries on a coherent subset of missions. Each subset is called User Operating Mode (USOM). The logical conditions to move from one USOM to another one are described by a state graph named USOM graph management. This graph defines the logical sequences of operating steps in which some missions start and some others end. At a given time, alarm decision is taken according to the availability of the elementary system components.

2.1 Services

A service is defined as a procedure whose execution results in the modification of at least one datum in the instrument data base, or/and at least one signal on its output interface. In the sense of bond graph methodology, the services correspond to some set of bond graph elements such: C (storage component), TF, (transformer elements), R, resistive element (pipe, valve,...), Se, effort source (pressure pump,...) , Sf, flow source (current generator,...). The services offered by the sensors (to measure) are assumed by effort (De) and flow (Df) detectors. The services provided by the equipment of sources of energy is represented by effort (Se) or flow (Sf) sources. The services provided by the information systems (controllers, ...) will be presented as block diagram since we assume that those systems do not exchange the power. The services offered by the functional role of the equipment (store, transform,...) is designated by the bond graph elements. Thus, the services as defined in the external model represent in a bond graph a set of elements necessary to the physical realization of this service.

2.2 USer Operating Mode (USOM)

In order to avoid the system to simultaneously perform incompatible services (initialization and production services for example), the set of services is organized into coherent subsets, called USOM. Each USOMi can be associated to a bond graph model noted $MBGi : USOMi \rightarrow MBGi$.

USOMs are given by a general classification of the operating modes of industrial devices: off operation, manual, ...An automaton of change user operating modes specifies USOM (initial USOM, and the others), and the conditions to change one USOM to another one. From this description, one can obtain a formal specification of the intelligent equipment.

2.3 Operating mode management

At a given time, the system runs in a nominal operating mode represented by the corresponding bond graph model MBG_i.

Let MBG the set of the bond graph models, and MBG_j the bond graph model corresponding to the j^{th} operating mode, and n the number of operating modes: $MBG = \{MBG_1, MBG_2, ..MBG_l, ...MBG_n\}$,

Let b the set of transition: $b = \{b_{ij}\}$, where b_{ij} indicates the required condition to move from MBG_i to MBG_j. It is represented by the Boolean variable ($b_{ij} \in \{0, 1\}$.

We consider that all conditions of changing mode (noted Cm) are correctly defined, i.e.

$$\begin{array}{c}\forall MBG_i(i = 1 - n) \in MBG, \exists j \\ \text{such as } b_{ij} \in Cm \text{ and } b_{ij} \neq 0\end{array} \quad (1)$$

The running operating mode can be represented as:

$$\begin{array}{c}MBG_j = \{s_{j1}(V_{j1}), s_{j2}(V_{j2}), ...s_{ji}(V_{ji}), ...s_{jm}(V_{ji})\} \\ = \{S_j\}/s_{ji}(i = 1, k) = \{\{C_{ji}\}, \{R_{ji}\}, \{TF_{ji}\}, \\ \{GY_{ji}\}, \{Se_{ji}\}, \{Sf_{ji}\}, \{De_{ji}\}, \{Df_{ji}\}\}\end{array} \quad (2)$$

m is the number of services (functions) offered to the smart actuator to accomplish the given operating mode associated to the MBG_j. k is the number of bond graph elements necessary for the physical realization of the ith service. V is the version of the serice.

Each USOM (or Bond graph model) MBG_j contains at least one service i.e. one bond graph element (if not the physical process does not exist).

3. FDI OF SMART ACTUATOR USING BOND GRAPHS

3.1 Bond graph representation of a monitored system

A monitored system can be represented as shown in figure 1. It consists mainly of two parts: a bond graph model and an information system. The bond graph model represent the energetic part of the system. It consists of the process plant, and the set of actuators. The actuators are modelled by a sources (of efforts and\or of flow). Se and Sf represent respectively a constant effort source and constant flow source (flow pump, voltage generator, ...). MSe and MSf represent respectively a modulated effort source variable and modulated flow source variable (controlled pump, controlled heater, ...). They depend on the output of the control system u. They are controlled by an external signal provided by a controller or the user. The sensors (represented in bond graph model by the detector of flow (Df), and detector of effort (De)) and control system (PID controllers, ...) form the information system. In the first system (energetic one), the exchanged power is represented by a half arrow (a bond) which label a power variables (effort and flow). In the second system (information system) the exchanged power is negligible, it is represented by an information bond, which is the same as in the block diagrams. It is shown as a full arrow on the bond graph and can represent the transmitted signal by a sensor, and by the control algoritm bloc.

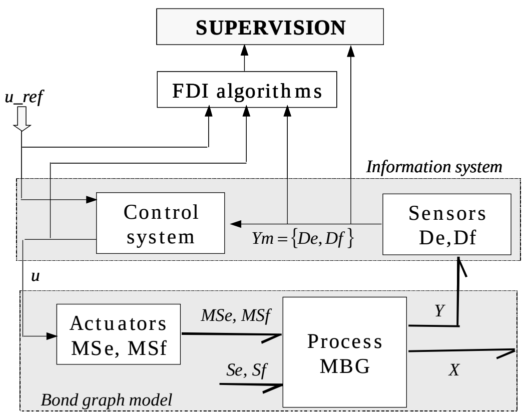

Fig. 1. Bond Graph representation of the monitored system

3.1.1. Description of the bond graph FDI system

A system may be described by a set of constraints F which represent the system model, a set of variables Z, and a parameters θ. The variables can be known or unknown: $S = S(F, Z, \theta)$.

(1) **Constraints.** The constraints F include informations about the structure (F_J), the behavior (F_B), the measurement (F_Y), and control system (F_C).

$$F = \{ F_J, F_B, F_Y, F_C \}$$

Structural equations F_J. The structural equations are deduced from junction equations. The number of F_J equations is equal to the sum of "0-junction", "1-junction", and the 2-ports elements, TransFormers (TF) and GYrators (TF and GY elements). $F_J \in R^{nj}$, n_j is the number of junctions:

$$F_J = \{F_{J0}\} \cup \{F_{J1}\} \cup \{F_{TF}\} \cup \{F_{GY}\},$$

Behavioral equations F_B. They describe the physical phenomena in bond graph elements.

$$F_B = \{F_C\} \cup \{F_I\} \cup \{F_R\}, \tag{3}$$

$F_J \in R^{n_e}$, n_e is the number of bond graph R,C, and I elements.

Measurement model F_Y expresses the way under which the sensors transform some state variables of the process into output signals: $F_Y = \{F_{De}\} \cup \{F_{Df}\}$ $F_Y \in R^{n_s}$, n_s is the number of sensors.

Control algoritms model F_C describes the controller's algorithm. $F_C(u, u\_ref, Ym, \theta_{reg}) = 0$. where θ_{reg} is a controller parameters, u_ref, and Ym represent respectively the set point value, and sensor outputs.

(2) **Variables.** The described set of constraints F apply to a set of variables Z, known (K) or unknown (X).: $Z = X \cup K$

The unknown variables are the power variables which label the bonds. The vector X containing all the power variables is

$$X(t) = \{e_1(t), f_1(t)\} \cup \{e_2(t), f_2(t)\} .... \\ ... \cup \{e_{nc}(t), f_{nc}(t)\} \tag{4}$$

where n_c is the number of components (I, R or C). Then the dimension of the vector X is $2 * nc$: $X \in R^{2*nc}$.

The subset K of known variables contains the control variables u, the variables whose value is measured by a sensor Ym and the supervised parameters (such as u_ref). $K = MSe \cup MSf \cup Se \cup Sf \cup Ym$. $MSe = F_{C1}(u), MSf = F_{C2}(u)$

Ym is the sensor output vector of dimension n_S.$Ym \in R^{n_S}$. n_S is the number of sensors.

Finally, $K \in R^l$, where $l = n_S + n_a$. n_a is the number of sources.

(3) **Parameters.** $\theta \in R^p$ is some parameters vector. In bond graph model it is associated to the characteristics of R,C, and I elements, i.e. flow coefficient, capacity value (which can be variable).

3.2 Fault indicators generations

The system FDI scheme is composed of a characterization and a decision step. Using a model based method, the first step generates a set of residuals called Analytical redundancy relations (RRA) which express the difference between information provided by the actual system and that delivered by its normal operation model. The residuals characterize the system operating mode: close to zero in normal operation, different from zero in faulty situations. Different approaches for the design of FDI procedures have been developed, depending on the kind of knowledge used to describe the plant operation.

The ARRs, which are used for the residual computation, can be derived from monitorable system using several approaches. (Chow and Willsky, 1984)(Cox et al., 1992). Here is used the algorithm generation using directly the bond graph model. It consists on following steps: a) Choose a junction, b) Find the corresponding ARR by writing its characteristic equations; d) Pass to the following junction. If the second ARR is independent from the first one, then keep it, else pass to another junction. e) Repeat (d) until the distinct signatures can be obtained.

The main idea is to associate to each constraint relation (constitutive equation) two indicators " *knv*" and " *unv*" ."*knv*" is the number of known variables and "*unv*" is the number of unknown variables. The goal is to decrease "*unv*" and increase "*knv*" such that: "*knv*" + "*unv*" = "$n$var"

where "*nvar*" $= 2n_C + n_S$ is the number of variables. n_C is the number of plant items in bond graph sense. The ARR is obtained when "*unv*" becomes zero.

4. APPLICATION TO A SMART PNEUMATIC VALVE

4.1 Description of the system under study

In order to show the practicality of the advocated approach, the methodology is applied to an actuator (figure 2) which represent a pneumatic valve chosen for DAMADICS benchmark (Bartys and De Las Heras, 2002).

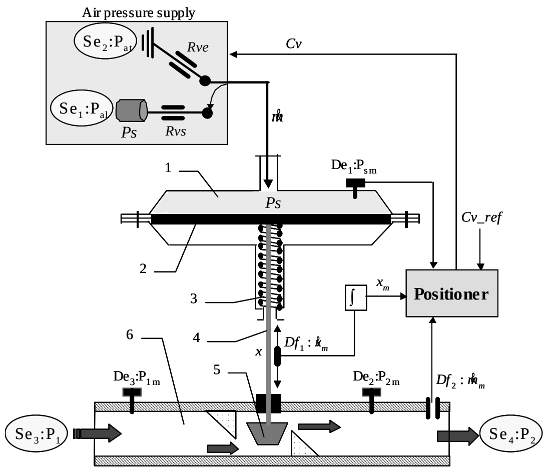

Fig. 2. Schematics of the actuator

The actuator consists mainly of a control valve, servo-motor, and a positioner with the pressure supply system. The control valve (5), allows to correct the flow flowing in the pipe (6) properly to maintain a desired set point. The driving force of the fluid is the difference of upstream pressure (Se_3) and downstream pressure Se_4. Those pressure are measured by the sensors D_{e3} and D_{e2}. The servo-motor consists of a pneumatic chamber (1), a spring (3), diaphragm (2), and a stem (4). This system is a compressible (air) fluid powered device in which the fluid stored in (1) acts upon the flexible diaphragm and spring to provide linear motion of the servomotor stem. The positioner is applied to eliminate the control-valve-stem miss-positions. The algorithm is based on PID controller algoritms given in (Bartys and De Las Heras, 2002). The air mass flow delivered by the supply air system depends on the state of supply (R_{vs}) and exhaust (R_{ve}) orifices. According to a control signal delivered by the positioner C_{v_ref}.The pneumatic chamber (1) is exposed to supply pressure $S_{e1} : P_{al}$ or is exposed to exhaust S_{e2}.

4.2 External Bond Graph models of the smart actuator

4.2.1. Bond graph model The bond graph model in normal operating regime is given in figure 3.

The inlet air mass flow $\dot{m}_{16}$ from the supply system to the pneumatic chamber is given by the constitutive equation of a modulated restrictors $R : Cvs$ and $R : Cve$. Those restrictor are modulated by the positioner output signal Cv. The compressibility effect and the air mass storage in the pneumatic chamber are modelled by the two-ports C-field (Cc). The transformation of pneumatic energy into a mechanical energy leading to the stem servo-motor displacement is modelled by the transformer TF whose the modulus Ae is the cross

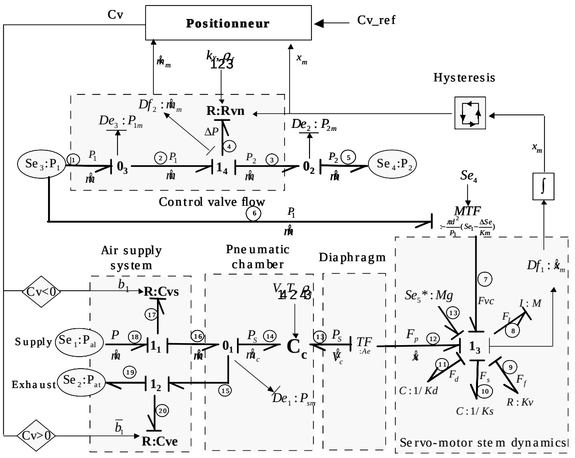

Fig. 3. Bond graph model of the smart actuator in normal operating mode

area of the diaphragm. The dynamic of the servo-motor steam is modelled by the conservation law energy represented by the "1_3-junction" linked to R,C and I elements. I, Kv, Ks, Kd, Se_5:Mg, Fvc, and Fp represent respectively the inertia due to the mass of the stem, the force due to the friction, the force due to the spring elasticity, the force due to the elasticity of the diaphragm, the gravity, the vena contracta force (which depends on the pressure of the controlled fluid, diameter of the plug, ...) and the active force. The flow through the control valve is modelled by the modulated R-elemnt R:Rvn. The resistance value $R : Rvn$ is the coefficient of hydraulic losses which depends on stem position x.

4.3 Missions and versions.

Based on objectives fixed by the technical specifications of the actuator, are defined not exhausted list of missions and associated services, i.e. bond graph elements, (table 1).

4.4 Operating modes management of the smart actuator

As said previously, the operating mode management given by the figure 4 allows the operator to be informed about conditions under which the passage from one USOM to another can be performed. In our approach and in complement of external model methodology, each USOM is represented by a bond graph model. It is an help for the operators to understand the basic physical principles, to visualize the physical phenomena of the process and to quantify each effect. Furthermore, the bond graph model is used to generate the alarm decision, and consequently the availability or not of the services (sensor, actuator or process fault)

N°	Missions	BG elements
1	To supply a pneumatic chamber with air pressure	Se_1,Cv,R:Cvs R:Cve,Se_2
2	To store the air in the pneumatic chamber	C:C_c
3	To transform a pneumatic energy into mechanical one	TF
4	To provide a motion of servo-motor steam	TF,C:1/Kd,TF C:1/Ks,R:Kv
5	To control the servo-motor steam position	Df1, Positioner
6	To control the flow of the fluid	Df2, Positioner
7	To provide a fluid in the pipe	Se_3, R : Rvn
8	To measure the pressure in the pneumatic chamber	De_1
9	To measure the inlet pressure in the pipe	De_3
10	To measure the outlet pressure in the pipe	De_2
11	To measure the servo-motor stem position	Df_1
12	To measure the control valve flow	Df2
13	To maintain equipments	

Table 1. List of missions and services

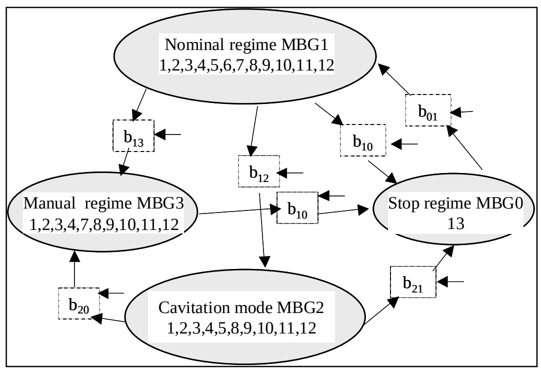

Fig. 4. Operating mode management of the smart actuator

The smart actuator correspond to the following not exhausted bond graph models. **MBG0: Stop Operating Mode.** In this mode, the actuator carries on the missions 13. Since the process is at rest (no power), the bond graph model doesn't represent an interest in this mode. **MBG1: Nominal regime.** The missions carried on are 1-12. The bond graph model is given in figure 3. **MBG2-Manual operating mode.** In this mode, the smart actuator carries on missions 1-4, and 7-12. **MBG3: Cavitation operating mode.** Cavitation results if fluid outlet pressure recovers to a pressure above the vapor pressure of the liquid. As the vapor cavities collapse, noise is generated and damage can occur. The main missions realized in this mode are 1-5, and 8-12.

Such organization increases the operational safety of the system and forbids the access to those USOM for which the meaningful services can not be run in good conditions. As an example, let us consider the current USOM, MBG1 and assume that the service 2 (To store the air in the pneumatic chamber) modelled by the two port C_C) is not available because of the leakage. Thus, according to figure 4 the passage to USOM MBG3 or MBG2 will be rejected since service 2 belongs to those operating mode. Only the passage to MBG0 is authorized. In the next section is given the alarm generation of the smart actuator FDI system.

4.5 Self monitoring of the smart actuator

4.5.1. Variables The vector X from the bond graph model (figure 3) is:

$$\begin{aligned} X &= \left[e_{17}\ f_{17}\ e_{20}\ f_{20}\ e_{13}\ f_{13}\ e_{14}\ f_{14}\ e_{8}\ f_{8} \right. \\ &\qquad \left. e_{9}\ f_{9}\ e_{10}\ f_{10}\ e_{11}\ f_{11}\ e_{4}\ f_{4} \right] \\ K &= \left[Se_1\ Se_2\ Se_3\ Se_4\ De_1\ De_2\ De_3\ Df_1\ Df_2 \right] \end{aligned} \tag{5}$$

4.5.2. Constraints

$$F = \{ F_J, F_B, F_Y, F_C \}$$

Based on the developped methodology, the following residuals are obtained:

$$\begin{aligned} r_1 &= \frac{\dot{P}_{sm}.n.P_{sm}}{\rho_a\,(Ae.x_m + V_0)} + \rho_a Ae.\dot{x}_m - b_1 C_v \sqrt{Se_1 - P_{sm}} \\ &+ \bar{b}_1 C_v \sqrt{P_{sm} - Se_2} = r_1(De_1, Se_1, Se_2, Df1, Cc\_f) \end{aligned} \tag{6}$$

where Cc_f represent the air leakage in the pneumatic chamber.

$$\begin{aligned} r_2 &= -Mg + Se_3 * (\pi.d^2).\left(Se_3 - \frac{(Se_3 - Se_4)}{Km} \right) \\ &+ Kv * \dot{x}_m + Ks * x_m - P_{sm} * Ae + Kd * x_m + M * \ddot{x}_m \\ &= r_2(Df_1, Se_3, Se_4, De_1) \end{aligned} \tag{7}$$

$$\begin{aligned} r_3 &= \rho_f \left(\frac{Df_2}{Kv(x_m)} \right) - Se_3 + Se_4 \\ &= r_3(Df_2, x_m, Se_3, Se_4, Df_1) \\ r_4 &= Se_3 - De_3, \quad r_5 = Se_4 - De_2 \end{aligned} \tag{8}$$

4.5.3. Decision procedure Based on the binary vector (table 2) of each component, all faults can be detected and isolated except the faults which may affect Se_1, and Se_2. Those components have the same fault signature.The signature fault is used for alarm generation for the operating mode management of the smart actuator given in figure 4. For example if the service "To store the air in the pneumatic chamber" which is associated with bond graph two ports C:Cc (table 1) is

	r_1	r_2	r_3	r_4	r_5
Se_1	1	0	0	0	0
Se_2	1	0	0	0	0
Se_3	0	1	1	1	0
Se_4	0	1	1	0	1
De_1	1	1	0	0	1
De_2	0	0	0	0	1
De_3	0	0	0	1	0
Df_1	1	1	1	0	0
Df_2	0	0	1	0	0
Cc_f	1	0	0	0	0

Table 2. Fault signatures

not available (because of leakage), the request "nominal regime mode" should be rejected as long as this service is not available. Thus, according to figure 4 the passage to USOM MBG3 or MBG2 will be rejected since service 2 belongs to those operating mode. Only the passage to MBG0 is authorized.

5. CONCLUSION

The external model provides a functional description, which is not sufficient to validate entirely the instrument behavior. In that sense, a bond graph as a complementary tool is introduced. The interest of this method rests on a physical knowledge of the actuator and a clear presentation of physical phenomena in order to improve monitoring and safety. Furthermore, the availability of services (associated to bond graph elements are directly generated using FDI procedures based on structural analysis of the bond graph model. The proposed methodology is applied to an actuator.

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