Fault Estimation and Fault Tolerant Control based on Bond Graph approach

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Summary
The paper presents a bond graph model-based approach to active fault tolerant control (FTC) that makes use of residuals of analytical redundancy relations (ARRs). It is shown that ARR residuals can be used for estimation of faults that can be isolated. Motivated by benefits of the Bond Graph (BG) tool as a useful method for multidisciplinary systems and which is characterized by structural, causal and behavioral properties, a new control accommodation of fault tolerant control enables to compensate the fault is designed.
The proposed approach focus on a diagnosis using the ARRs and a fast estimation. In order to illustrate the effectiveness of the proposed approach, an hydraulic system with two tanks has been studied.
Key words:
Bond Graph, Active fault tolerant control, analytical redundancy, Fault detection and isolation, Fault estimation, Fault accommodation.

1. Introduction

Engineering systems are becoming more and more complex such as aero engines, vehicle dynamics, manufacturing systems, chemical processes, electric machines and industrial electronic equipment and so forth, are safety-critical systems. The maintenance of this kind of systems is expensive and difficult to perform. As a result, the Fault Detection and Isolation (FDI) procedures become then necessary and even obligatory in some situations to increase the productivity and the benefits [1], to improve operator safety and protect the environment.
Furthermore, it is paramount to implement fault-tolerant control (FTC) for minimizing performance degradation and avoiding dangerous situations.
The main objective of fault-tolerant control (FTC) is to ensure that the system operates with and without faults.
FTC is carried out through fault accommodation and/or system reconfiguration. In fault accommodation, the objective is to control the system within actual constraints. It is largely applied when the fault can be isolated, estimated, and is not severe. It consists in maintaining the system running with the faulty components. System reconfiguration is generally applied when the fault cannot be estimated. In this instance, the system is reconfigured (e.g by changing the set point) to transit the system from one mode to another.
Two types of FTC are known in the literature, passive approach (e.g. robust control) and active approach (e.g. adaptive control). The passive control treats the problem of robustness to faults using the similar tools as those used for robustness to uncertainties and disturbances [2]. In active FTC, faults have to be detected and diagnosed (in terms of location and parameters estimation) by FDI systems, then subsequently the controller is redesigned. A bibliographical review of active FTC can be established in [3]. A different active FTC approach that also used to avoid the isolation and the estimation of faults has recently been announced in [4]. In AFTC, different fault tolerant design as the Pseudo Inverse Model (PIM), the Linear Quadratic (LQ) approach and the Linear Matrix Inequality (LMI) are presented in [5]. Furthermore, modelling is an important and difficult step because of the complexities of these systems. Bond graph (BG), is an effective tool for modeling, and it has been proven useful for fault detection and isolation (FDI) in dynamical systems [6]. The objective of using the BG tool that it's enable to couple both structural diagnosis results with control analysis [7].
In this article, FDI procedures are based on Analytical Redundancy Relations (ARRs) [8][9] for which mathematical model is needed.
The goal of this paper is to generate an active FTC problem using graphical approaches based on bond graph representation, that makes use of ARR residuals. The proposed approach is established using generation of ARR based on bond graph and which is used to detect and estimate failures. When the fault has been isolated and its size estimated, the fault can be accommodated by creating a new control into the faulty system.
In the present work, a Pseudo Inverse Model law is presented to compensate failure effects [10][11]. This paper

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presents a bond graph model-based approach to active FTC that makes use of ARRs residuals.
The outline of this work is organized as follows: Section 2, introduces the concept of fault detection and isolation based on bond graph and the generation of ARR. Section 3, presents the proposed AFTC strategy based on ARR residuals to detect and estimate faults. Section 4, illustrates Two tanks example in order to show the effectiveness of our proposed approach. Simulation and fault scenarios are carried out to confirm the proposed methodology in section 5. Finally, concluding remarks are presented.

2. BG for Fault Detection and Isolation

This section looks into fundamental elements of bond graph approach and how it can be used for FDI.

2.1 Bond graph Modelling

The Bond graph has been defined by Henry Paynter in 1961 [12], subsequently developed by Karnopp in 1975 [13], Rosenberg in 1983[14] and then Breedveld in 1985 [15]. It is an excellent tool to model complexe and multidisciplinary systems.
The bond graph modeling is based on the exchange of power in a system, which in normally the product of an effort variable and a flow variable. This exchange takes place in bonds represented by a simple line.
The concept of power p(t) can be depicted as indicated in Eq. (1):

$$p(t) = e(t).f(t) \quad (1)$$

Where e(t) and f(t) are the effort and the flow respectively. This equation illustrates the energy transfer in the system using power links. A link power is symbolized by a half-arrow, whose orientation indicates the direction of power transfer.

2.2 Analytical Redundancy Relations

A primordial step in FDI is the evaluation of the time history of residuals serving as fault indicators.
The Analytical Redundancy Relations (ARRs) are relationship between the only known variables only (i.e. inputs, sensors, parameters) [16]. Theses relations express the difference between information provided by the actual system and that delivered by its normal operation model.
Analytical Redundancy Relations (ARRs) can be derived off-line from a BG of a physical model in a systematic manner and ARR residual, the general form of an ARR is given by

$$f(k) = 0 \quad (2)$$

The number of redundancy relations derivable from any system model is equal to the number of sensors in the system. An ARR is then written as

$$ARR: f(D_e, D_f, S_e, S_f, MS_e, MS_f, \theta) = 0 \quad (3)$$

Where
- k is the set known variables(sources and measured values specified by detectors),
- D_e, Df are effort and flow sensors,
- S_e, S_f are effort and flow sources,
- MS_e and MS_f are modulated effort and flow sources,
- θ is represented a vector of all parameters.

Residual symbolized by r is the numerical value of ARR (evaluation of ARR) that can be written as follow:

$$r - f(k) \approx 0 \quad (4)$$

The numerical evaluation in real-time, can serve as fault indicators [17]. Obtaining ARRs in closed symbolic form is difficult because the elimination of unknouwn variables from the model is not a trial task. However, ARRs need always represent physical laws, it is not easy to write then down directly from the mathematical model of the system.
The generation of analytical redundancy relations (ARRs) from a bond graph model is summarized a stepwise procedure in the following algorithm [18]:
Step 1. The bond graph model is made in integral causality.
Step 2. The unknown variables are eliminated by covering the causal paths from the bond graph elements to the detectors.
Step 3. The ARRs of detector redundancy are written by expressing energetic evaluations on junctions 1 and 0.
Step 4. The obtained ARRs at the previous step are composed of two parts: a nominal part r, which describes the residual, and an uncertain part called a, which represents the uncertainties. This uncertain is used to calculate the normal operating thresholds.

3. Proposed Fault Tolerant Control Strategies

The FTC strategy can be either system reconfiguration or fault accommodation, depending on the fault information. In this paper, we focus on the fault accommodation.

3.1 Fault accommodation

Fault accommodation is an active Fault Tolerant Control (FTC) technique that modify the controller law after a fault has occurred and relies on a faultless operation of the sensors and the actuators [19].

Once the fault has been isolated and its size estimated, the fault can be accommodated by reconstructing a new control into the faulty system so that the fault is compensated and the system remaining faulty generates a desired output behavior. Moreover, ARRs set up for fault detection, isolation and fault estimation can also be used for fault accommodation [20].
The principal of our proposed approach presented the fault accommodation scheme in Fig.1 that shows the interplay of fault diagnosis and controller redesign. Before applying the FTC, a FDI procedure and fault estimation should be studied in the following section.

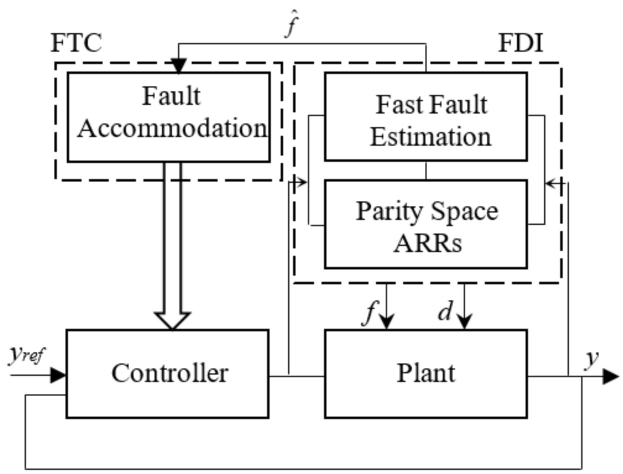

Fig. 1 Fault accommodation for proposed approach

The elaborated estimation approach is based on analytical redundancy relations as it will be designed in the sequel. Considering the linear model (5):

$$\begin{cases} \dot{x} = Ax(t) + Bu(t) + Ef(t) + d(t) \\ y = Cx(t) \end{cases} \tag{5}$$

Where $x \in \mathbb{R}^n$ is the state vector, $u \in \mathbb{R}^m$ represents the set of input variables, $y \in \mathbb{R}^p$ is the set of output variables and $f \in \mathbb{R}^r$ is the set of fault variables (actuator faults in our case), $d \in \mathbb{R}^q$ is the disturbance. $A \in \mathbb{R}^{n*n}$, $B \in \mathbb{R}^{n*m}$, $C \in \mathbb{R}^{n*p}$ and $E \in \mathbb{R}^{n*m}$ are known parameter matrices and supposed to be of full rank. The system $\sum(C, A, E)$ defined in (5) is supposed to be controllable/observable and the state matrix A is invertible.

3.2 Diagnosis part based on ARRs

We are interested in this section, to the analysis and design problem of an active fault-tolerant controller, which includes a fault diagnosis (FDI) followed by a controller accommodation strategy.

In our previous work [21], we have synthesized fault detection and isolation (FDI) for hybrid system, the latter is not evident because hybrid system consists both discrete mode change and continuous nonlinear behavior.
In table 1, it is given the structural equations deduced from bond graph modelling of process (show Fig.2). For each mode, we have generated the ARRs for FDI by bond graph model. We combined the equations presented in table 1 to eliminate unknown variables. The known variables are available from sensors and actuators, so we generate the set of residuals in which the appeared variables are all known.

Table 1: Structural equations for normal mode

N	Junction	Structural equations
1	Junction 01	$\begin{cases} e_1 = e_2 = e_3 = e_4 = De_1 \\ Msf - f_{C_1} - f_{R_1} - f_4 = 0 \end{cases}$
2	Junction 1	$\begin{cases} f_4 = f_5 = f_6 \\ e_4 - e_5 - e_6 = 0 \end{cases}$
3	Junction 02	$\begin{cases} e_6 = e_7 = De_2 \\ f_6 - f_7 = 0 \end{cases}$

The first junction 0_1 equation as follows:

$$Msf - f_{C_1} - f_{R_1} - f_4 = 0 \tag{6}$$

By replacing the flow f by its expression generated from the BG after eliminating the unknown variables, the residual 1 is obtained as follow:

$$ARR_1 = Msf - C_1 \frac{dDe_1}{dt} - \frac{De_1}{R_1} - \frac{De_1 - De_2}{R_2} \tag{7}$$

The equation (7) shows that the residual rl is sensitive to these elements (MSf, C_1, De_1, De_2, R_1 and R_2). Consequently, when fault is occurred in each elements described above, the residual r_l becomes different of zero.
The second junction O_2 gives us the following equation:

$$f_6 - f_7 = 0 \tag{8}$$

According to these equations, we can deduce the residual r_2:

$$ARR_2 = \frac{De_1 - De_2}{R_2} - C_2 \frac{dDe_2}{dt} \tag{9}$$

The equation (9) shows that the residual is sensitive to these elements (De_1, De_2, R_2 and C_2).

3.3 Estimation of actuator fault

The information which component parameter contributes to which ARR in some system mode can be described in a structural Fault Signature Matrix that is called FSM [22].

Table 2: Structural fault signature matrix of the BG model

Residuals	ARR1	ARR2
Msf (pump)	1	0
R_1	1	0
R_2	1	1
R_3	0	0
R_4	0	0
C_1	1	0
C_2	0	1
De_1	1	1
De_2	1	1

As it shows in (Table 2) on the FSM, the components Msf, C_1 and R_1 have the same signature ”10”. The sensibility of the residuals to these faults is not the same, so these three faults can be isolated using the developed procedure of fault estimation and isolation.
That is, the parametric fault cannot be isolated by inspecting the structural FSM. Considering an estimate of the actuator fault f(t).
To achieve the fast fault estimation, this theorem proposed by [23] is given herein.

Theorem 1: If there exist symmetric positive definite matrices $P \in ¡^{n*n}$, $Q \in ¡^{r*r}$ and matrix $F \in ¡^{r*p}$ which check up the following conditions:

$$A^T P + PA - PCR^{-1}CP + Q < 0 \tag{10}$$

$$E^T P = FC \tag{11}$$

then the fault estimation algorithm is presented by Eq. (12):

$$\hat{f}(t) = -\psi F r(t) \tag{12}$$

The proof of Theorem 1 can be referred to [23]. Actuator fault estimate using the Theorem 1 can be written as

$$\hat{f}(t) = -\psi F \int_t^{t_f} r(\tau) d\tau \tag{13}$$

Where

$$F = E^T P C^{-1} \tag{14}$$

Furthermore, we can confirm that fault estimation with the residual integration, obtained by Theorem 1 ameliorate considerably estimation fastness.

3.4 FTC strategies

Once a fault has been detected and its size estimated by the diagnosis unit, a controller reconfiguration is needed to guarantee some prescribed specifications. In [4], Allous and Zanzouri propose to use a Luenberger observer and to feed output residuals into an inverse system in order to avoid the isolation and the estimation of faults. In [24], Allous propose also a novel fault tolerant control design in the presence of multi-actuator and parameter faults using the Lyapunov function and a linear matrix inequality approach. In [25], Najari and all have synthesized a graphical AFTC using a Proportional Integral (PI) controller and an additive control law which is a Pseudo Inverse Model (PIM) law that compensates failure effects.
In our work, we have propose to compensate the fault so that the fault can be accommodated by designing a new input into the faulty system and the system remaining faulty makes a desired output behavior.
To accomplish the fault accommodation law, we have synthesized a fault tolerant control which is based on a pseudo inverse control strategy [26].
The tolerant control law can be exhibited as :

$$u_{FTC} = u_{nom}(t) + u_{add}(t) \tag{15}$$

where $u_{FTC}(t)$ is the new redesigned control, $u_{nom}(t)$ is the created control law in nominal case to reaches system performances given in this case by the state feedback control and $u_{add}(t)$ is the additive law to be elaborated in faulty system to satisfy nominal performances. Such as, $u_{add}(t)$ is computed like that additive fault effects can be corrected. Therefore, the following condition must be checked up :

$$Bu_{add}(t) + Ef(t) = 0 \tag{16}$$

Knowing that matrix B must be of full rank. Given the actuator fault estimation presented in the last section, this additive control law is given herein :

$$u_{add} = -B^{+} E \hat{f}(t) \tag{17}$$

where B^+ is the pseudo-inverse of the control matrix B calculated as following :

$$B^{+} = \left[B^T B\right]^{-1} B^T \tag{18}$$

B^T is the matrix transpose.
The nominal control law can be written as follow :

$$u_{nom}(t) = -Kx(t) \tag{19}$$

The feedback control gain K is calculated using the Linear Matrix Inequality (LMI) resolution. The gain matrix K is defined by Eq. (20):

$$K = R^{-1}B^{T}P' \tag{20}$$

where the matrix P is obtained by solving the following Riccati Eq. (21):

$$A^{T}P + PA + Q - PBR^{-1}BP < 0 \tag{21}$$

where

$$P > 0, \quad Q > 0 \text{ and } R > 0$$

Using the Schur Complement, we can symbolize this inequality by LMIs as follows:

$$\begin{bmatrix} A^{T}P + PA + Q & PB^{T} \\ B^{T}P & -R \end{bmatrix} < 0 \tag{22}$$

4. Application : Two tank system

To validate the theoretical results and to show the controller efficiency of our proposed approach, an hydraulic system with two tanks is described in Fig.2.

4.1 System description

The two-tank system is adapted from [27]. The process is shown in Fig. 2. This system is composed of:

- Two tanks T_1 and T_2 with the same section S are connected by pipes which can be controlled by different valves.
- A pump P that delivers a liquid to tank T_1.
- Three switching valves V_1, V_2 and V_3.
- Two level sensors: one level sensor that measures h_1 and the other level sensor measures h_2, the liquid level in tank T_2.

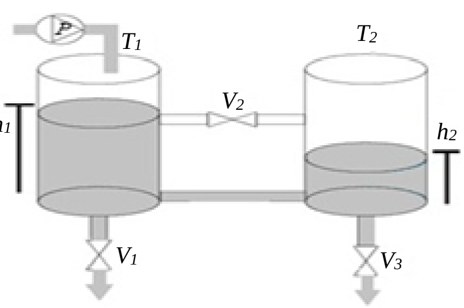

Fig. 2 Two-tank system Scheme

The first tank T_1 is feeded by a controlled pump modeled as a source of a flow MSf : u to keep water level constant. Each tank has an hydraulic capacity $C_1 = \frac{A_1}{\rho.g}$, $C_2 = \frac{A_2}{\rho.g}$ respectively, A_1 and A_2 are the section of each tank, ρ is the density of water, g is the gravity. The two sensors are represented by De_1: y_1, De_2: y_2 (water level in each tank). The bond graph model of the system is given in Fig.3.

The failure here is represented by an additive actuator fault. The state equation of the faulty bond graph model is written as Eq. (23).

$$\begin{cases} \dot{x}_1 = -\frac{1}{C_1}\left(\frac{1}{R_1}+\frac{1}{R_2}\right)x_1 + \frac{1}{C_2R_2}x_2 + u + f \\ \dot{x}_2 = \frac{1}{C_1R_2}x_1 - \frac{1}{C_2R_2}x_2 \\ y_1(t) = \frac{1}{C_1}x_1 \\ y_2(t) = \frac{1}{C_2}x_2 \end{cases} \tag{23}$$

The matrix gain K for the nominal control is obtained from the LMI resolution

$$K = \begin{bmatrix} 0.3333 & 0 \end{bmatrix} \tag{24}$$

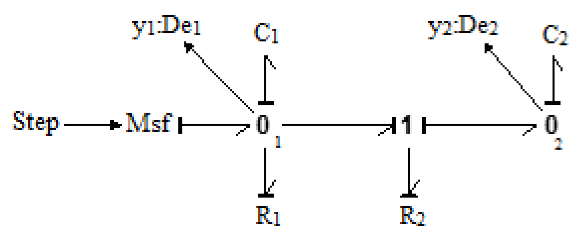

Fig. 3 Bond graph model of two-tank system

5. Simulation results

The simulations have been performed by the software Matlab and 20-sim. The numerical values of system parameters are shown in table 3. The control input (pump flow) is $u(t)$= 0.0045m^3/s and initial conditions are equal to 0. The considered actuator fault is represented by Fig.5, the fault start at (t=4s) with an amplitude of 0.001m^3/s.

Table 3: Numerical values of system parameters

Parameters	Description	Values	Units
C_1	Tank section C_1	0.05	$m^4.s^2/Kg$
C_2	Tank section C_2	0.06	$m^4.s^2/Kg$
R_1	Resistance	1	$pa.s/m^3$
R_2	Resistance	1	$pa.s/m^3$

The normal evolutions of residuals are presented in Fig.4. Simulation time is fixed to 10s. From Fig.5, it can be seen that the residual signal response is different from zero when the fault occurred, therefore the actuator fault is detected

and the residual r_1 is sensitive to the introduced fault. This is confirmed by the FSM presented in table 2.
The real trajectory is very close to its estimate as seen in Fig.6 and this estimation allows a fastness of the actuator fault signal.

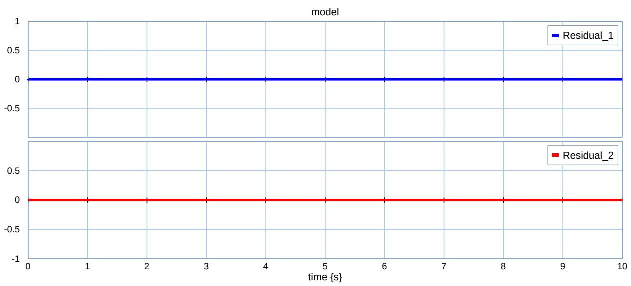

Fig. 4 Residuals in normal operation

A fault is simulated at the pump (modelled by MSf in BG).

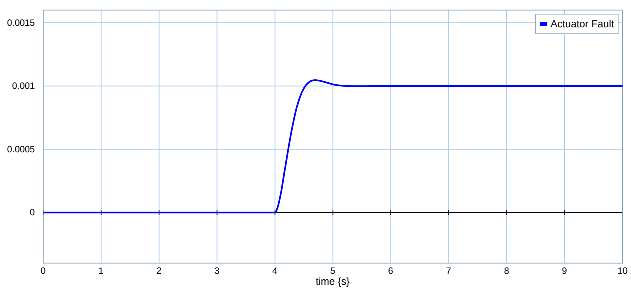

Fig. 5 Residual in failure mode (Pump failure)

Fault detection and estimation are illustrated by figures Fig.5 and Fig.6. Simulation results of our system behavior without and with control loop are given by Fig.7.

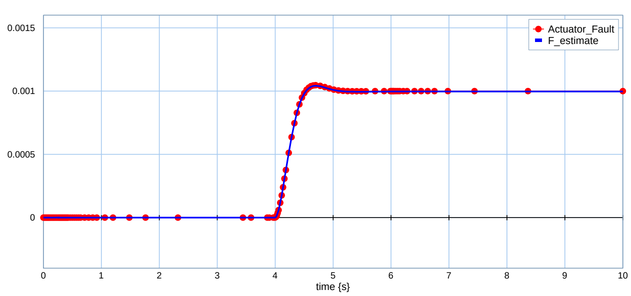

Fig.6 Fault signal and its estimate.

The simulation in Fig.7 display that our proposed fault accommodation using the fast estimation is fast and improve the rapidity of the recovery fault. So we can deduce that the used ARRs an accurate to achieve a better accommodation.

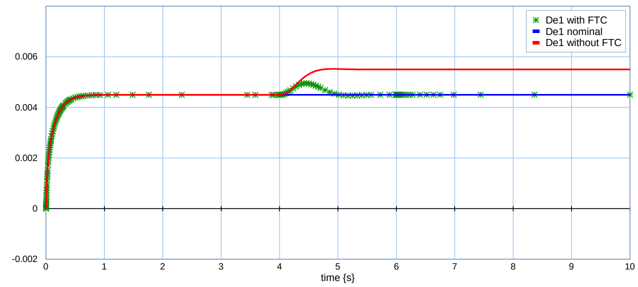

Fig.7 Output signal with and without compensation

The active fault tolerant control evolution is shown by Fig.8.

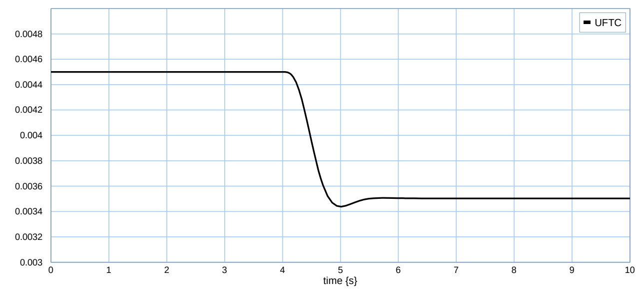

Fig.8 The Fault tolerant control u_{FTC}

6. Conclusion

In this paper, an estimation of actuator fault and an Active Fault Tolerant Control system has been studied using the bond graph as a dynamic and efficient modelling tool. Thanks to its graphical, structural and causal properties, BG methodology can be used not only for dynamic modelling but also for Fault Detection and Isolation (FDI). From simulation results, we can see clearly that failure effects are compensated using both tolerant laws. Firstly, the additive control that compensate the fault presented by the pseudo inverse method. Secondly, a nominal state feedback control presented to reaches system performances. An implementation system is well justified by the simulation results was detected and fast estimated through an analytical redundancies relations (ARRs).

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