FAULT CHARACTERIZATION FOR MULTI-FAULT OBSERVER-BASED DETECTION IN TIME VARYING SYSTEMS

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Abstract: Useful fault information, such as the amplitude and the sign, occurring during a time variable dynamic process are of capital importance to proceed correctly to fault compensation. The existing observers in literature, providing residues signals containing information on the presence or not of faults, do not take into account all of the faults when those occur at very close moments, which leads to an incorrect eventual compensation. This consideration is very significant for a correct dynamic control.
In this paper, the characterization of the fault form in the time varying dynamic systems based on observers is proceeded to consider the detection of several faults some is their incidence moment and to take into account their amplitudes. The study of the several faults succession at the same moment or different moments, and of its consequences, is detailed. It is highlighted then the contribution of this characterization to fault detection and resolution where the interest to exploit these resolution in precise fault detection is shown.

1 INTRODUCTION

The fault detection and predictive maintenance in dynamical systems have a capital importance in various industrial domains: engineering systems, biochemical process, sensors and actuators, manipulator robots and various domains of precision (V. Venkatasubramanian and Kavuri, 2003a), (V. Venkatasubramanian and Kavuri, 2003b), (V. Venkatasubramanian and Yin, 2003). The increase complexity of these systems have motivate the development of different approaches of fault detection in intend of supervision. This development was proved by a large number of works as studied in (Vemuri and Polycarpou, 1997), (Shen and Hsu, 1998), (Xiong and Saif, 2000), (R. Hadj Mokhneche and Vigneron, 2005), (Kuo and Golnaraghi, 2003) and (Rosenwasser and Lampe, 2000). The model-based approaches for fault detection and isolation suppose that the failures and degradations correspond to changes in some parameters of the underlying unknown process (V. Venkatasubramanian and Kavuri, 2003a), (Lee et al., 2003). These changes can be used as faults and all parameters which are liable to change must be detected and identified on line in order to proceed, for example, to their compensation (Isermann, 1995).

Among the model-based approaches for fault detection, the residual generation problem is that most elaborate in the carried out research works (Vemuri and Polycarpou, 1997), (Lee et al., 2003), (Shen and Hsu, 1998), (Xiong and Saif, 2000), (Lee et al., 2001) where the residues (or residues signals) are quantities null or close to zero and when a fault appears in a system parameter, they become different from zero. The observer-based plans are the most attractive of residual generation strategies in which each observer is designed to be sensitive to only one fault signal. In that follows, the problem position is given, then the functioning of an observer with its residue signal is presented. A detailed study on the fault characterization is established, where some new definitions are given. The different types of detection are described and therefore the contribution of the fault characterization to fault detection resolution is highlighted. Finally, a conclusion on the impact of the fault characterization on fault detection and compensation is given.

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2 THE PROBLEM POSITION

The two only currently available information via the observers are the representative signal shape of the fault (residue signal indicating fault) and the measurable value of its amplitude. It is possible to detect with the same residue signal several faults, occurring at different instants, therefore successively, or at the same instant (figure 1). However, if we have not adequate tools to detect and to distinguish the various faults (between F_{A_i} and F_{B_i}, see figure 1), it is necessary to describe the fault correctly. In that goal, it is proposed a characterization of fault, which will make it possible to evaluate its amplitude and its time location, and to check its influence on the preceding fault and/or the following one. This characterization will also make it possible to conclude on the presence of one or several faults in the signal, to determine the local amplitude in the one fault case or total amplitude in a several faults case, and by consequence to proceed to a correct compensation according to the fault event instants and fault amplitudes. This is significant especially when it is about real time compensation where the dynamic system must be corrected immediately.

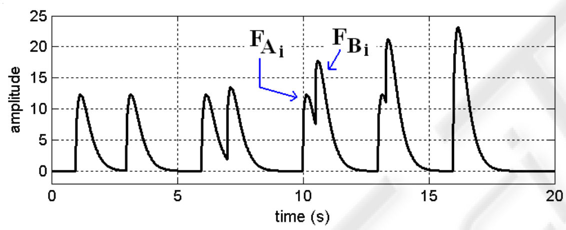

Figure 1: System with parameter observer.

3 OBSERVER BEHAVIOR AND RESIDUE SIGNAL

The behavior of linear or nonlinear observer with respect to the faults works according to the following principle : when a fault occurs on one or some of the system parameters, given that each parameter have its own observer, the corresponding observer can detect the fault and the residue signal changes value from zero (or close to zero) to a non-zero value, then it takes a zero value again (or close to zero) after a considerable short duration.

The figure (2) formalizes an example of an observing system (Kuo and Golnaraghi, 2003), (Rosenwasser and Lampe, 2000), where x_1 and x_2 are state variables and where x_1 is the speed

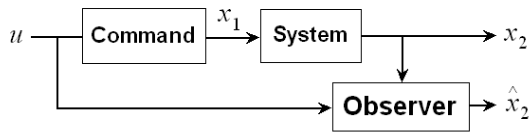

Figure 2: System with parameter observer.

to observe. The observer is designed to follow x_1 by knowing the signals x_2 and u. The output signal of the system is x_2, and the observer signal is represented by $\hat{x}_2$ which is called the residue signal.

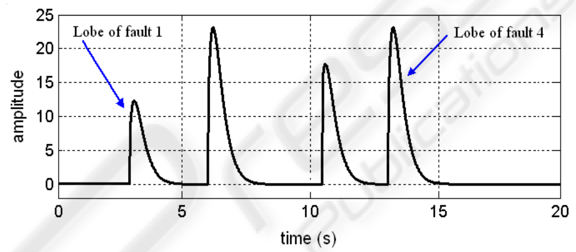

Figure 3: Residue signal : one parameter observation.

With the system as indicated on figure (2) in presence of faults, one can obtain the simulation residue signal which is given on figure (3) where four simulated faults are detected at instants 5, 10, 12 and 16.

The importance here is not to give the transfer function of the system and doing development to found characteristic equation of $\hat{x}_2$, but to explicit the residue signal in order to extract pattern characteristics of some importance. Thus, fault characterization is concerned by the study of this residue signal and precisely the *Fault Lobe* which represents the residue signal variation from its initial zero or close to zero value to next zero or close to zero value as shown on figure (3). However, as it will be seen in section 5, when faults occur at very close instants, one cannot distinguish the lobes and will see all them in the same one lobe. Thus, in a general way, one cannot know if a lobe corresponds well to only one fault or several ones.

Because the residue signal can be analyzed and then some compensator can in such a way compensate the parameter which underwent this fault, this compensation is reliable only if the characteristics of the fault are known such as the amplitude (or gain) and the nature (lobe representing only one fault or several faults).

Suppose that θ is the parameter to be controlled so that θ_0 is the nominal value (normal functioning of the system). Let θ_1 the current parameter value. The error can be defined by :

$$\varepsilon = |\theta_1 - \theta_0| \tag{1}$$

If during control the process, the parameter θ undergoes a first fault, its observer can detect it and the compensator will be able thereafter to compensate the parameter while bringing back ϵ to zero.

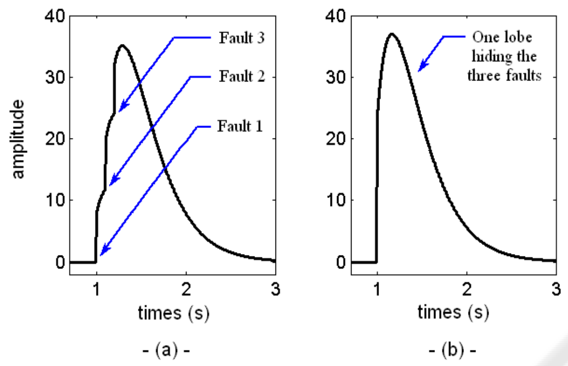

Figure 4: Residue signal showing faults occurring at closer (a) and very closer (b) instants.

The delay between the instant detection of fault and the instant of the end of compensation, so during compensation, there can occur n other faults with, possibly, various amplitudes, sometimes on the same parameter. If these faults occur at very close instants (figure 4b), the residue signal will not shows clearly the lobes related to each fault (figure 4a). If the faults instants are even closer, the residue signal will give a single lobe hiding thus all the faults lobes. In other words, these faults are not correctly detectable, the compensation command signal which is in progress will not be correct too.

In the next section, it will be highlighted the characterization of a fault, to be an assistance tool to the faults detection, where all situations of faults occurrence and types of detection will be discussed.

4 FAULT CHARACTERIZATION

A system parameter can undergo one or several faults spread out in time. We have shown in section 3 that if the faults occur at the same instant or very closer instants, they can be assimilating to only one fault but with amplitude more significant than that of each fault separately (figure 4b). If the faults occur successively, therefore at different instants, a *robust and precise observer* must be able to detect them clearly, to distinguish them and to have a sufficient resolution of detection, i.e. to detect two clear successive faults over the one smallest possible duration of incidence, noted FID (see Definition 3).

4.1 Definitions

One defines the new following useful terms. Suppose that i is the fault recurrence number and n is the number of faults.

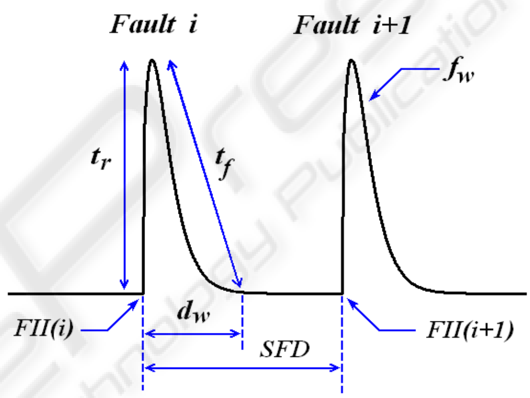

Figure 5: Fault characterization in observer residue signal.

The figure (5) shows two well distinguished successive faults (i) and ($i+1$) at different instants, occurring on a system parameter in fault, where all notations are described in the definitions below.

Definition 1 The instant when the residue, previously equal to zero or close to zero, starts to change its value to reach an amplitude different from zero is defined as FII (Fault Incidence Instant). Therefore $FII(i)$ is the fault incidence instant of fault i, and $FII(i+1)$ is the fault incidence instant of following fault $i+1$ (figure 5).

Definition 2 The duration running out between two successive faults i and $i+1$ (figure 5), is noted SFD (Successive Fault Duration) and defined by :

$$SFD = FII\,(i+1) - FII\,(i) \tag{2}$$

Definition 3 The duration running out between the instant $FII(i)$ of fault i and the instant when the residue (corresponding to fault i) takes the value zero or close to zero is defined as FID (Fault Incidence Duration) (figure 6).

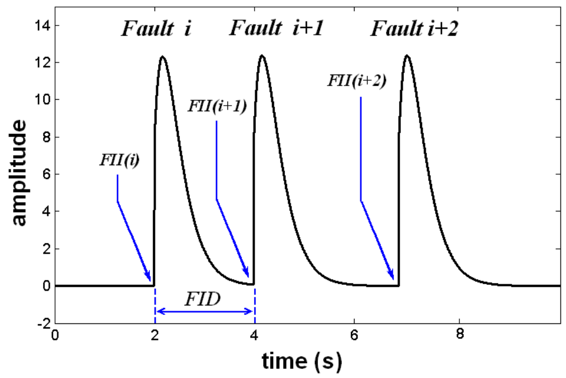

Figure 6: Fault Incidence Duration (FID).

Definition 4 The duration between the fault incidence instant $FII(i)$ and the instant when the residue signal reaches the first maximum value of its amplitude (corresponding to fault i) is noted t_r (figure 5). The duration between the instant when the residue signal has the maximum value of its amplitude and the instant when it reaches the zero value or close to zero is noted t_f (figure 5).

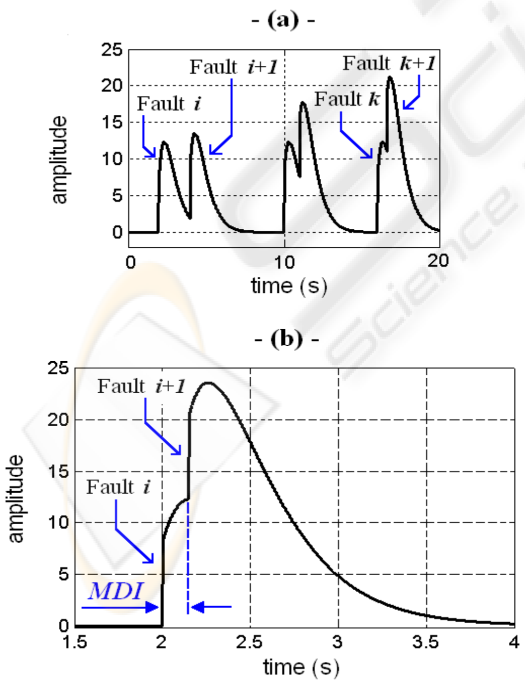

Figure 7: a) Two successive faults. b) Minimum Duration Incidence (MDI).

If the residue signal contains two faults i and $i+1$, one can suppose that at the time when the fault i took place, that is to say during the variation of the residue corresponding to this fault, another fault $i+1$ intervenes (figure 7a). This assumption leads us to definition 5.

Definition 5 The duration between the instant $FII(i)$ and the moment when finishes the raising time t_r of fault i, which also corresponds to the beginning of the raising time t_r of the following fault $i+1$, is defined as MDI (Minimum Duration of Incidence) (figure 7b).

Definition 6 The wrap of fault which covers the duration ($t_r + t_f$) is called fault wrap and noted f_w (figure 5).

Definition 7 The duration between the instant $FII(i)$ and the moment when this residue come back to zero or close to zero is named a wrap duration and noted d_w (figure 5). It is defined by :

$$d_w = t_r + t_f \tag{3}$$

Remark : The term d_w corresponds to fault complete wrap and will be used in the case of one fault presence in residue signal. The term FID corresponds to definitely detected fault and will be used in the case of multi-fault presence in residue signal.

5 TYPES OF DETECTION

Consider the observer residue signal obtained by simulation and plotted in figure (8). Six faults are simulated at instants 1, 3, 6, 6.5, 10 and 10.18 zoomed. The first two ones are zoomed in figure (9), the two second ones in figure (10) and the two last ones in figure (11). Notice that the simulated amplitudes of all faults are equal.

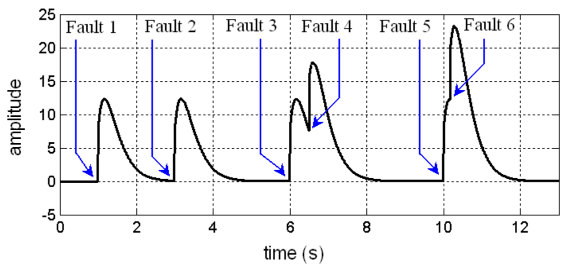

Figure 8: Multi-faults residue signal.

One can notice that the simulation of the figure (8) shows well the impact of the event of a fault $i+1$ for the length of time d_w (see figure 5) of the preceding fault i. Here, the fault-4 intervening during fault-3 lobe took a more significant amplitude than envisaged (value 17.5 instead of 12), even thing for the fault-6 intervening during the fault-5 lobe. But the fault-2 taking place apart from the fault-1 lobe has a correct amplitude.

While Basing on the diagram of the figure (8) representing the observer signal, three types of detection can be distinguished and which are complete, partial and skewed detection.

5.1 Complete Detection

If no fault occurs for the length of duration d_w of fault i (figure 5), the fault will be clearly and properly detected. This means that the SFD is equal to FID.

Therefore, to have a clear fault without overlapping with the next fault $i+1$ (figures 5 and 9), and in order to obtain the real values of different faults amplitudes, the following condition (4) must be satisfied :

$$SFD_{cd} \geq FID \tag{4}$$

If the condition (4) is checked, the detection will be complete (figures 5 and 9) and the compensation will be able to take place knowing that the fault detection was correct.

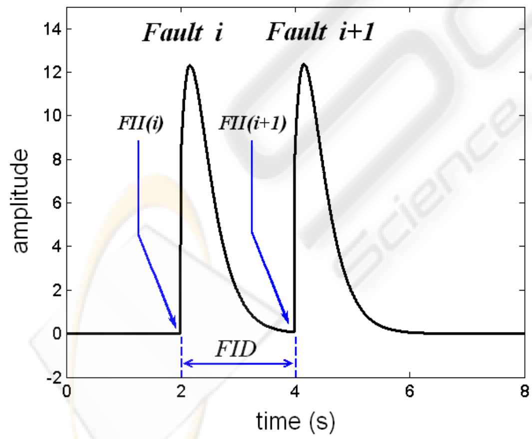

Figure 9: Limit Complete Detection of a fault.

The figure (9) shows the limit of complete detection which corresponds to equation (5) :

$$SFD_{lcd} = FID \tag{5}$$

5.2 Partial Detection

The partial fault detection corresponds to a new fault detection during the failing time t_f of the earlier fault (figure 10). Thus, the detection of a next fault $i+1$ for the length of duration d corresponding to the duration between the beginning of the time t_f of fault i and the occurrence of the fault $i+1$ during same time t_f is considered as partial detection. The duration d can be defined then by the equation (6) :

$$MDI \leq d < FID \tag{6}$$

where MDI is minimum duration of incidence (see Definition 5).

Although the observer has an enough fast response time to detect the fault, the time t_f remains rather long compared to the raising time t_r (see figure 5). This means that if other faults occur in the duration d_w, they will be partially represented in the residue. The amplitudes of faults pile up to give to the amplitude of last fault a different value from what it was normally to be. This value is not inevitably the sum of the amplitudes of all faults, but it is more significant and is not representative. Thus, if the compensation takes place will not be correct taking into account the fluctuations in the parameter enduring these faults.

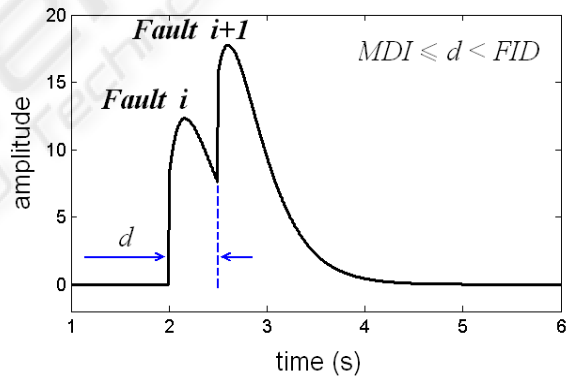

Figure 10: Partial detection of a fault.

5.3 Skewed Detection

Skewed detection (figure 11) corresponds to a new fault detection (fault $i+1$) during or at the end of the raising time t_r of the earlier fault (fault i).

6 PROPERTIES

Knowing that every fault has its own wrap, and if several faults occur with the condition (7)

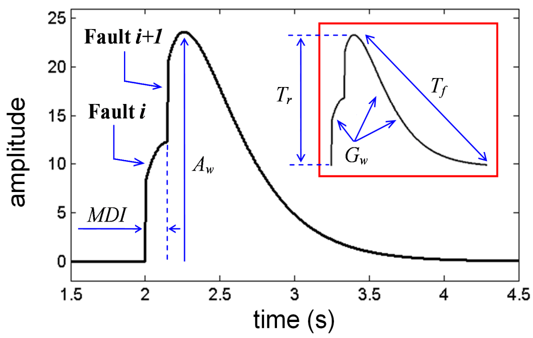

Figure 11: Skewed detection of a fault.

$$SFD < MDI \tag{7}$$

all the wraps of faults are reduced to one global wrap G_w which is covering the all wraps of the faults as shown on figure (4b). That gives the impression thus to detect only one fault with one wrap. The global wrap, expressed by equations (8) and (9), is defined by G_w which is expressed of local wrap function F_{w_i} of each fault i corresponding to its duration t_r :

$$G_w = F_{w_1} + F_{w_2} + \cdots + F_{w_n} = \sum_{i=1}^{n} F_{wi} \tag{8}$$

$$\begin{aligned} F_{w_1} &\triangleq (f_w)^1_{t_r} \\ F_{w_1} &\triangleq (f_w)^1_{t_r} \\ &\vdots \\ F_{w_n} &\triangleq (f_w)^n_{t_r} \end{aligned} \tag{9}$$

where n is the number of faults and F_{w_i} the wrap of fault i for duration t_r ($i = 1 \cdots n$),

Really, for n faults, the global raising time T_r corresponds to the pile up of the local times t_r and the global failing time T_f corresponds to the pile up of the local times t_f, of all faults which are dissimulated under the global fault G_w. So, T_r and T_f are nonlinear functions which can be expressed by equations (10) and (11).

$$T_r = \sum_{i=1}^{n} \alpha_i t_{r_i}\ , \quad i = 1 \cdots n \tag{10}$$

$$T_f = \sum_{i=1}^{n} \beta_i t_{f_i}\ , \quad i = 1 \cdots n \tag{11}$$

where α_i and β_i are coefficients, t_{r_i} the raising time of fault i and t_{f_i} the failing time of fault i.

In normal functioning conditions of observer, the residue signal, corresponding to system parameter having undergone these various faults in skewed detection case, will have an end value of amplitude A (figure 11) which is neither that of the first fault nor that of the last one. It does not represent also the sum of the all amplitudes. Or an online compensator intervening during MDI consider only the first fault with its own amplitude, which is incorrect. The total lobe, result of the twinning of the all faults lobes, have the wrap amplitude A_w which can be written in a nonlinear function expressed by (12).

$$A_w = \sum_{i=1}^{n} c_i A_i \tag{12}$$

where A_i is amplitude of fault i, and c_i its coefficient.

7 OBSERVER RESOLUTION IN MULTI-FAULT DETECTION

The encountered problems in partial and skewed detections types has conduce us to consider the MDI as determining and crucial element for fault detection resolution. So, one of the consequences of the fault characterization is the resolution which an observer must take into account to have the best resolving power between two successive faults. This resolving power will characterize the observer precision or resolution to detect two successive completely fault and without overlapping. So to differentiate between the precision from the various observers, it is enough to determine the MDI of each one then to compare them to conclude which is smallest. Thus, a better observer would be that which detects all the faults with their real amplitude some is duration SFD (see Definition 2), and the best observer resolution would be that for which the maximum of faults are properly (completely) detected during the time MDI.

8 CONCLUSION

A system parameter fault represented in a residue signal by a lobe is characterized in order to determine its behavior which enable us to treat it correctly and effectively. The important characteristics of the fault were largely detailed and new definitions were established and which will allow to proceed to a correct future compensation.

It was highlighted the impact of the occurrence of several successive faults, at very close instants or at different instants, on the amplitude of residue signal. It was given conditions to respect for detecting correctly one or more faults. It was proven the influence of the detecting response time on fault detection and compensation.

Two properties are deduced, first the global amplitude of faults occurring at very close instants represented by the residue amplitude can be represented by a nonlinear function with coefficients which remains to be determined, and secondly the resolution to detect two successive completely faults without overlapping. These two properties can be interesting for the fault compensation.

To carry out a correct detection of all possible faults, it is necessary that the observer would be precise and able to distinguish the various faults, some is instant of incidence, with a good resolution of detection. In other words, the observer must have a good resolving power.

REFERENCES

Isermann, R. (1995). Model base fault detection and diagnosis methods. *Proceedings of the American Control Conference*, 3:1605–1609.

Kuo, B. C. and Golnaraghi, F. (2003). Automatic control systems. *Eds John Wiley and Sons, New York*.

Lee, I. S., Kim, J. T., Lee, J. W., Lee, D. Y., and Kim, K. Y. (2001). Inversion based fault detection and isolation. *Proceedings of the 40th IEEE Conference on Decision and Control*, 2:1005–1010.

Lee, I. S., Kim, J. T., Lee, J. W., Lee, D. Y., and Kim, K. Y. (2003). Model-based fault detection and isolation method using art2 neural network. *International Journal of Intelligent Systems*, 18:1087–1100.

R. Hadj Mokhneche, H. M. and Vigneron, V. (2005). Hybrid algorithms for the parameter estimate using fault detection, and reaching capacities. *The 2nd International Conference on Informatics in Control, Automation and Robotics ICINCO, Barcelona, Spain*, 4:289–293.

Rosenwasser, E. N. and Lampe, B. P. (2000). Computer controlled systems: Analysis and design with process-orientated models. *Eds. Springer, New York*.

Shen, L. C. and Hsu, P. L. (1998). Robust design of fault isolation observers. *Automatica*, 34:1421–1429.

V. Venkatasubramanian, R. Rengaswamy, K. Y. and Kavuri, S. N. (2003a). A review of process fault detection and diagnosis. part i: Quantitative model-based methods. *Computers and Chemical Engineering*, 27:293–311.

V. Venkatasubramanian, R. R. and Kavuri, S. N. (2003b). A review of process fault detection and diagnosis. part ii: Qualitative models and search strategies. *Computers and Chemical Engineering*, 27:313–326.

V. Venkatasubramanian, R. Rengaswamy, S. N. K. and Yin, K. (2003). A review of process fault detection and diagnosis. part iii: Process history based methods. *Computers and Chemical Engineering*, 27:327–346.

Vemuri, A. T. and Polycarpou, M. M. (1997). Robust nonlinear fault diagnosis in input-output systems. *International Journal of Control, Taylor and Francis*, 68:343–360.

Xiong, Y. and Saif, M. (2000). International journal of robust and nonlinear control. *Automatica*, 10:1175–1192.