Application of the Method of Dynamic Decomposition for Recognition of Multiple Faults in the Large Scale Systems

Jan M. Kościelny, Michał Z. Bartyś

Institute of Automatic Control and Robotics, Warsaw University of Technology
Warsaw, Poland (e-mail: jmk@mchtr.pw.edu.pl, barty@mchtr.pw.edu.pl).

Abstract: The problem of the on-line multiple fault isolation in diagnostics of large scale systems has been presented in this paper. Considerations about possibilities of recognition of multiple faults making use from the knowledge about signatures of single faults have been made. Distinction between simultaneous faults and series of faults has been introduced. The necessary condition of diagnostic reasoning assuming occurrence of multiple faults has been formulated. It has been shown that multiple faults appearing simultaneously or within short time intervals may be correctly isolated under assumption of single faults if the subsets of faults suitable for their isolation are disjunctive. An industrial example of reasoning about multiple faults has been presented.

Keywords: fault isolation, multiple faults, on-line diagnostics, industrial processes.

1. INTRODUCTION

Most of the known FDI methods were developed under assumption of appearance of single faults (Gertler, 1998; Chen and Patton, 1999; Patton, Frank and Clark, 2000; Korbicz et al., 2004). This assumption allows significant simplification of the algorithms of fault isolation. However, these algorithms may be successfully applied only for the relatively simple systems consisting of a few components. In such systems, the probability of occurrence of single faults is much higher then occurrence of multiple faults. But in case of complex industrial installations the assumption about single faults is not admissible. One have to consider multiple fault existence and its consequences, taking into account the scale of the plant, huge number of components, its reliability figures, etc.

Recognition and isolation of multiple faults was studied relatively rarely. Clark (1989) and Frank (1987) have been presented a study of diagnosing of multiple faults of instruments and actuators with the application of the banks of observers for residual generation and classic logic for decision making procedures about faults. Other kinds of faults have not been taken into consideration what seriously limited the practicability of this approach.

The method of directional residuals (Gertler, 1998; Patton, et al. 2000), method of detection filters (Chen and Speyer, 1999) and application of decoupled Kalman filters (Adam-Medina et al., 2003) potentially gives substantial possibilities of isolation of multiple faults. But these approaches require system models assuming influence of faults on residuals. Practically, such models are not possible to yield for complex non-linear systems.

AI methods (Cordier, et al., 2000a, 2000b; Nyberg and Krysander, 2003) called as model-based diagnosis (MBD) as well as methods based on Reiter (1987) theory allow isolate single and multiple faults (de Kleer and Williams, 1987; Hwee Tou Ng, 1991; Hamscher et al., 1992; Gorny, 2001; de Kleer and Kurien 2003). The diagnoses are generated as the minimal hitting sets of the all minimal conflict sets. These approaches takes advantages by taking into consideration fault compensation effects. These approaches found application only for diagnostics of relatively simple systems (Gorky, 2001; Hwee Tou Ng, 1991) because of its complexity and huge development costs. A new approach to multiple fault diagnosis based on combination of diagnostic matrices, graphs, algebraic and rule-based models has been shown by Ligeza and Koscienly (2008).

Multiple faults may appear either simultaneously or sequentially. Simultaneously appearing faults are beyond any doubt most difficult to recognise. Under assumption of statistical independence of faults, the phenomenon of simultaneously faults seems to be extremely rare. From the other hand, one should keep in mind, that this is typical situation in the start-up phase of almost each diagnostic system of large scale system. In this phase, all previously appearing and still existing faults are seen by the diagnostic system as multiple and simultaneous. The lack of the appropriate procedures handling these faults may lead to improper action of diagnostic system. Therefore, this problem should be solved. Moreover, it is clear that in large scale systems consisting of thousands of apparatus, the existence of simultaneously faulty devices one can describe as a quite typical situation.

Generally, one can state that there are a serious issues that should be solved in the diagnostics of multiple faults. In this paper, the effort has been taken to find answers on the following questions:

- Is it possible to correctly recognise multiple faults by analysis of single faults only?
- Which conditions should hold to guarantee obtaining of truth diagnoses?
- How to infer about multiple faults?
The analysis of the issues of recognition of multiple faults will be based on following set of assumptions:

1° Data from the faulty system states are not available. This is very important assumption. It is understandable that acquisition of data from the all faulty system states is practically impossible.

2° The analytical models of the process affected by faults are not known. In case of the large scale systems acquisition of such models is practically impossible due to its mathematical complexity and huge modelling costs.

3° The possibility of compensation of influences of faults on residuals will be neglected. The probability of compensation of influences of faults on residuals is practically very low. Compensation of influences of faults on residuals may take place only in case of occurrence of multiple faults affecting the same residual. If the faults are detected by single residuals, and if residuals are independent then probability of occurrence of multiple faults in short period of time is very low.

4° Probability of quasi-concurrent occurrence of multiple faults is considered.

5° Symptoms uncertainty is not taken into considerations. This assumption has been taken for simplification of the description of the multiple faults problems. However, this assumption is not justified in practice. Application of fuzzy logic or Bayes theory (Kościelny, 2001; Korbicz et al. 2004) may be effectively used to solve symptoms uncertainties problem.

6° Dynamics of the symptoms is not taken into consideration. This assumption has been taken for simplification of the description of the basic problem discussed in this paper. Neglecting the dynamics of the symptoms may lead to generation of false diagnoses and therefore should not be generally omitted. The methods assuring the correctness of diagnoses in case of symptom delays are presented in (Kościelny, 2001; Kościelny et al. 2007, 2008).

7° Residuals are binary evaluated. It is the most frequent approach applied for diagnostics of large scale systems. This assumption provides relative easiness in obtaining of binary diagnostic matrices from the expert knowledge. However it is known, that application of tri-valued evaluation of residuals may help to enhance fault distinguisability factors (Kościelny, 2001; Kościelny et al. 2006). Extension of the considerations given below on the case of tri-valued symptoms is possible.

2. BASICS OF FAULT ISOLATION

2.1 Faults and diagnosed system states

Let us define the set of possible faults – \( F \). Faults are considered as destruction events lowering the quality of overall or part of the system.

\[
F = \{ f_k : k = 1,2,...,K \} \tag{1}
\]

Faults should be detected and isolated in diagnostics process. Define system state \( z(f_k) \) related to fault \( f_k \):

\[
z(f_k) = \begin{cases} 
0 - \text{fault free state} \\
1 - \text{faulty state} 
\end{cases} \tag{2}
\]

Define the set of existing faults \( F(I) \) as follows:

\[
F(I) = \{ f_k \in F : z(f_k) = 1 \} \tag{3}
\]

Assume that the diagnosed state of the system is determined by the states of all the faults from the set \( F \).

\[
z = \{ z(f_1), z(f_2),..., z(f_K) \} \tag{4}
\]

Set \( Z \) of all states \( z_i \) of diagnosed system:

\[
Z = \{ z_i : i = 0,1,...,I \} \tag{5}
\]

where:

\[
Z_{(m)} = \{ z_i \in Z : \sum_{k=1}^{K} z(f_k) = m \} \tag{6}
\]

is the subset of system states with \( m \) multiple faults. The state \( z \) of diagnosed system may be uniquely described by the set \( F(I) \), consisting of faults occurred in this particular state.

2.2. System state and fault signature

The set of diagnostics tests is used for fault isolation purposes. Every diagnostic test generates diagnostic signals \( s_j \) based on process variables (Fig. 1).

![Fig. 1. Block diagram of a diagnostic test based on the model of the system](image)

The results of all the diagnostic tests are collected in the set of diagnostic signals \( S \):

\[
S = \{ s_j : j = 1,2,...,J \} \tag{8}
\]

Inverse inference necessary to isolate faults by means of diagnostic signals is based typically on the \( a'\text{priori} \) knowledge of relation faults-symptoms:

\[
R_{FS} \subset F \times S \tag{9}
\]

Most frequently, relation faults-symptoms has a form of binary diagnostic matrix (Fig. 2). Every matrix element is defined as follows:

\[
r(f_k, s_j) = \begin{cases} 
0 & \text{if } (f_k, s_j) \notin R_{FS} \\
1 & \text{if } (f_k, s_j) \in R_{FS} 
\end{cases} \tag{10}
\]

The element of diagnostic matrix is equal to 1 if diagnostic signal \( s_j \) points out fault \( f_k \). The columns of diagnostic matrix are called signatures of faults. Signatures may be interpreted as a reference patterns of particular faults in case of single faults.

\[
V(f_k) = \{ r(f_k, s_j) : s_j \in S \} \tag{11}
\]
Fig. 2. Binary diagnostic matrix

The references of diagnostic signals of all system states may be defined similarly (Fig. 3). The full matrix of system states consists of the references of diagnostic signal states in the faulty and healthy states of the system. The distinction is made between faulty states with single, double, triple, quadruple etc. faults. The matrix of system states in case of single faults is identical to the binary diagnostic matrix.

Fig. 3. The matrix of system states

The column vector of reference diagnostic signals values is defined as the particular state of the system signature.

\[ V(z_j) = \{ v(z_j, s_j) : s_j \in S \} \] (12)

The states are indistinguishable if the state signatures are identical. The state signatures may be based on binary diagnostic matrix. Typically, (Gertler, 1998; Kościelny, 1995, 2001) the union operator of all fault signatures in particular system state is used for creating elements of system state signature.

\[ v(z_i, s_j) \equiv v_q = \bigcup_{k: f_k \in F(l_i)} r_{ik} \] (13)

This method of signature design does not assume the possibility of the influence of the fault compensation phenomenon on residual values.

2.3. Diagnosing based on assumption of single and multiple faults

In case of diagnostics assuming appearance of exclusively single faults, the diagnosis points out faults which signatures match the actual values of diagnostic signals.

\[ DGN^s(F) = \{ f_k \in F : \forall z_j \in S_i : r(f_k, s_j) \} \] (14)

The faults are indistinguishable if the fault signatures are equal. In case of diagnostics assuming multiple faults, the diagnosis points out those system states that conform with achieved values of diagnostic signals.

\[ DGN^s(Z) = \{ z_j : \forall z_j \in S_i : v(f_k, s_j) \} \] (15)

Those states are indistinguishable by the given set of diagnostic signals.

3. MULTIPLE FAULT ISOLATION BASED ON ASSUMPTION OF APPEARANCE OF SINGLE FAULTS

3.1. Sequence of faults

In case of huge technological installations consisting of thousands of apparatus, the states with multiple faults are not exceptional. Taking into account that diagnostics is carried out in on-line mode, the diagnosis \( DGN \) in a moment \( n \), should isolate the subset of faults that just have appeared since previous diagnosis has been generated:

\[ DGN^s_n = F^1 - F^1_{n-1} = \{ f_k : [z(f_k)_n = 1] \cap [z(f_k)_n-1 = 0] \} \] (16)

It is unlikely that more than one fault will appear within very short time interval. Therefore, if faults appear in sequences with time intervals longer than the time necessary to formulate subsequent diagnoses, the diagnoses generated by assumption of single faults may be classified as allowable. It should be stressed however, that the set of allowable diagnostic signals must be reduced by the signals that are sensitive to the isolated fault immediately after each subsequent diagnosis. Inclusion of all previously excluded diagnostic signals should be done immediately after recovering of fault free state of the system. Set \( S \) is dynamically modified according to principles given by Kościelny (1995, 2001).

Fig. 4. Illustration of case of sequential faults

3.2. Simultaneous faults

The diagnostic inference may fail if two or more faults occur in the time interval shorter than the time needed for diagnosis formulation. In this case the set of diagnostic signals is inconsistent with the set of signatures of possible faults. Therefore, diagnosis in the form (15) can not be formulated. It can happen that in particular case, the signature of the state with double or triple faults may conform to the signature of the single fault. In this case false diagnosis will be generated.

Fig. 5. Illustration of case of simultaneous faults
If the diagnostic inference is based on the availability of the full set of diagnostic signals then mentioned above reasoning scheme is correct. In practice, the only subset of diagnostic signals is sufficient to undertake the decision about faults, even in complex diagnosed systems. The principles of reasoning about multiple faults based on Dynamic Decomposition of diagnosed System (DDS) method are given below. DDS method is used in DTS method (Kościelny, 1995, 2001) and F-DTS (Kościelny et al., 1999, 2001, Korbicz et al., 2004). Decomposition of diagnosed system is an operation of dynamic creating of appropriate subsystem defined by the sets of possible faults and diagnostic signals sensitive to these faults. The subsystem is created immediately after appearance of first fault symptom. Further diagnosis is conducted in the frames of this subsystem.

\[(s'_1) = 1 \Rightarrow F^1 = \{f_i \in F : < f_i, s'_j > \in R_{FS}\} \]  (17)

The following subset of diagnostic signals is created for the recognition of the state with faults:

\[S^1 = \{s_j \in S : F^1 \cap F(s_j) \neq \emptyset\} \]  (18)

where:

\[F(s_j) = \{f_i \in F : < f_i, s_j > \in R_{FS}\} \]  (19)

Let’s see that the subsets \(F^1\) and \(S^1\) are determining the subset of diagnostic relation:

\[R_{FS} = \{< f_i, s_j > \in R_{FS} : f_i \in F^1, s_j \in S^1\} \]  (20)

The diagnosis based on this relation is as follows:

\[DGN(F)S^1 = \{f_i \in F^1 : \forall s_j \in S^1 = r(f_i, s_j)\} \]  (21)

If another fault appears in the system in the same time and if this fault does not belong to \(F_1\) then it will be detected by one of the diagnostic signals sensitive to this fault. Similarly to (18), the new subset of possible faults will be created:

\[(s'_2) = 1 \Rightarrow F^2 = \{f_i \in F : < f_i, s'_j > \in R_{FS}\} \]  (22)

and a subset of diagnostic signals suitable for fault isolation:

\[S^2 = \{s_j \in S : F^2 \cap F(s_j) \neq \emptyset\} \]  (23)

Both subsets determine the subset of diagnostic relation:

\[R_{FS} = \{< f_i, s_j > \in R_{FS} : f_i \in F^2, s_j \in S^2\} \]  (24)

If the diagnostic sets \(S^1\) and \(S^2\) are disjunctive:

\[S^1 \cap S^2 = \emptyset \]  (25)

then both faults will be isolated correctly in separate fault isolation processes. In this case the relation subsets \(R^1_{FS}\) and \(R^2_{FS}\) are also disjunctive.

Conclusion: Multiple faults appearing simultaneously or within short time intervals will be correctly isolated under assumption of single faults if the subsets of faults suitable for their isolation are disjunctive.

4. EXAMPLE OF DIAGNOSING OF MULTIPLE FAULTS UNDER ASSUMPTION OF SINGLE FAULTS AND APPLICATION OF DDS METHOD.

Consider steam-water line of power boiler. Steam-water line is a part of technological installation located between the boiler itself and the inlet of the fresh steam to the power turbine. Steam-water line has symmetrical structure. It consists of two parts (upper and lower). The synoptic diagram of the steam-water is given on Fig.6. Installation consists of the set of following subsystems: steam superheater (1), cooling water injector (2) and control valve of cooling water (3). Components (2) and (3) are constituting steam attemperator assembly.

Steam is overheated in the set of superheaters to the temperature much higher then steam have in the boiler outlet. This leads to drying the steam. The superheater is an assembly consisting of a set of steel pipes mounted in the boiler and heated by combustion gases. The steam temperature should be controlled very carefully due to optimisation demands of the work-hour efficiency. Too high steam temperature may cause accelerated wear or even damage of the elements of steam-water line. The steam temperature is lowered by process of injection of cool water into the steam flow. The steam attemperator assembly is used for this purpose. The throttling valve in attemperator controls the cooling water inflow.

The problem of fault detection and isolation in the steam-water line was described in (Kościelny and Syfert, 2000; Korbicz, et al., 2004) where the sets of faults, sets of detection algorithms as well as fault isolation method was given. Fault detection in water-steam line was based on mixture of methods based on partial models of installation (in the form of neural networks and fuzzy models) as well as on heuristic knowledge. Binary diagnostic matrix of the steam-water line is given on Fig. 7. The set of diagnostic tests is divided into three subsets separated with double horizontal lines. First subset contains common tests for elements of both parts of steam-water line. Two subsequent subsets contain tests detecting faults accordingly in upper and lower part separately.

Consider exemplary case of simultaneously appearance of faults \(f_5\) and \(f_{20}\). Following binary diagnostic matrix shown on Fig. 7 one has to expect appearance of diagnostic signal values \(s_{12}, s_{13}, s_{20}, s_{21}\) = 1 and zero values of remaining diagnostic signals. In this case, diagnosis based of the binary diagnostic matrix (Fig. 7) assuming single faults is not possible at all because values of diagnostic signals do not conform to any fault signature.

Let now consider case of diagnosing based on dynamically defined subsets of diagnostic relations. Assume that faults \(f_5\) and \(f_{20}\) were pointed out appropriately by occurrence of diagnostic signals \(s_{12}\) and \(s_{21}\). Following sets of possible faults will be created:

\[(s_{12}) = 1 \Rightarrow F^1 = \{f_5, f_{13}, f_{14}\} ; (s_{21}) = 1 \Rightarrow F^2 = \{f_{19}, f_{20}\}. \]

Respectively, corresponding subsets \(S^1\) and \(S^2\) of diagnostic signals are disjunctive:

\[S^1 = \{ s_{12}, s_{13}, s_{21} \} , \quad S^2 = \{ s_{19}, s_{20}, s_{21} \}. \]

Diagnoses formulated from the subsets of binary diagnostic matrix (Fig. 8) according to Eq. (21) will point out both faults i.e. \(f_5\) and \(f_{20}\). Reduction of the size of considered subsets of diagnostic relations compared to the size of the full binary diagnostic matrix significantly lower computing power needed to carry out diagnostic procedures.
5. SUMMARY

The chosen problems of the diagnostics of multiple faults have been discussed in the paper. Following conclusions have been formulated:

Diagnosis about multiple faults generated under assumption of occurrence of single faults is correct if the faults occur sequentially with the occurrence intervals longer than the time necessary to formulate subsequent diagnoses.

Application of dynamic decomposition of diagnosed system method gives the opportunity of isolation multiple faults in spite of diagnosing assuming existence of single faults. Even
simultaneously appearing faults may be isolated correctly under assumption of occurrence of single faults in case if the subsets of diagnostic signals suitable for its isolation are disjunctive. Application of the DDS method reduce significantly the computational power needed for formulation of diagnoses about single and multiple faults. Diagnostic reasoning assuming occurrence of multiple faults must be applied only in this cases where the subsets of diagnostic signals suitable for its isolation are not disjunctive.

ACKNOWLEDGEMENTS

This work has been financed from the research fund for years 2007-2009 as a research, investigation and development project „DIASTER”.

REFERENCES


