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Diagnostic Relation Determination Based on the Extended Description of the Process and Diagnostic System Components

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Zatrudniony jest w Instytucie Automatyki i Robotyki, Politechniki Warszawskiej. Zajmuje się badaniami w dziedzinie diagnostyki procesów przemysłowych oraz zastosowań logiki rozmytej. Jest głównym autorem systemu diagnostycznego DIAG oraz jednym z głównych autorów zaawansowanego systemu monitorowania i diagnostyki AMandD.

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Abstract

The paper presents the method of describing the connections between the process components and the elements of a diagnostic system with the use of the set of relatively simple relations. Such a structure created at the configuration stage includes the information about the diagnostic relation. The method of an automatic determination of the preliminary diagnostic relation based on connections written down in the hierarchical structure was proposed. Considered algorithm was illustrated based on a real application for simple, exemplary process.

Keywords: fault diagnosis, diagnostic relation, expert knowledge.

Wyznaczanie relacji diagnostycznej na podstawie rozszerzonego opisu elementów procesu oraz systemu diagnostycznego

Streszczenie

W artykule zaprezentowano metodę opisu struktury połączeń elementów procesu oraz systemu diagnostycznego za pomocą stosunkowo prostych i intuicyjnych relacji. Tak utworzona na etapie konfiguracji systemu diagnostycznego struktura zawiera informacje o relacji diagnostycznej. Zaproponowano metodę automatycznego wyznaczania wstępnej relacji diagnostycznej za podstawie zależności występujących w zaproponowanej strukturze hierarchicznej. Rozważany algorytm został zaprezentowany na rzeczywistym przykładzie prostego stanowiska.

Słowa kluczowe: diagnostyka uszkodzeń, relacja diagnostyczna, wiedza ekspercka.

1. Introduction

The paper considers the commonly used class of diagnostic systems which reasoning algorithms structure complies with the one presented in Fig. 1. It is assumed that there are some kinds of detection algorithms available which calculate diagnostic signals S. They are based on the analysis of current process variables X, according to the relation R^{XS}. At the second stage, the diagnostic reasoning is performed. It is conducted according to the diagnostic relation R^{SF} describing the relation between the existing faults and the observed diagnostic test results. As a result of the reasoning, the system generates the set of fault certainty factors (F) which formulate the final diagnosis about the system state.

One can distinguish the following main configuration stages of such processes: (a) definition of the set of considered faults and the set of available process variables, (b) determining the set of partial models, (c) designing the set of diagnostic tests (for fault detection purpose), (d) diagnostic relation determination, (e) diagnostic system decomposition (in the case of complex systems).

The algorithms and designing methods related to stages (a) - (c) were subjects of many research and are now quite well recognized [2, 3]. The biggest problem is the implementation of stages (d) and (e). During these stages it is necessary to make some decisions, depending more or less on the objective knowledge about the process variable set, the available knowledge about the object, the established requirements, and also on the subjective knowledge of the diagnostic system engineer.

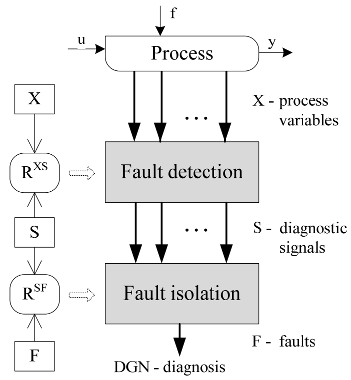

Fig. 1. The diagram of diagnosing
Rys. 1. Ogólny schemat wnioskowania

A proper definition of the diagnostic relation determines the possibility to carry out the proper fault isolation. In the discussed group of systems, the diagnostic relation is usually defined by an expert, basing on the process knowledge, algorithms of the residual calculation, influence of individual faults on the operation / performance of constituent elements of installation / system, etc. The process of relation definition is not easy.

On the other hand, the diagnosed process is usually too complicated to apply its more formal description that could be further used for the automatic determination of the diagnostic relation. Sometimes, it is possible to apply some kind of behavioural model. However, creation of such a model is usually a very time-consuming process. It is reasonable in the case, when such a model is also used for other purposes, e.g., is directly connected with designing and / or running detection algorithm procedures [1].

There was a need to design a relatively simple method of supporting the diagnostic system design without the necessity of introducing many additional parameters to the ones already used. The paper introduces an extended description of the structure of the process and diagnostic system components. It also presents the basic methods of the automatic determination of the diagnostic relation based on such a description.

2. System components and its relations

The following basic components are present in the description of almost each diagnostic system:

- The set of faults understood as destructive events causing the decrease of the process operation quality:

$$F = \{f_k : k = 1,2,\dots,K\}. \quad (1)$$

- The set of process variables, i.e. measured and control signals, utilized for the fault detection:

$$X = \{x_i : i = 1,2,\dots,I\}. \quad (2)$$

- The set of diagnostic signals, calculated on the outputs of detection algorithms (tests), which can be based on the process models as well as the signal analysis:

$$S = \{s_j : j = 1,2,\ldots,J\}. \quad (3)$$

- Relation R_{XS} defined on the Cartesian product of the sets S and X:

$$R^{XS} \subset X \times S. \quad (4)$$

Expression $<x_i,s_j> \in R^{XS}$ denotes that a value of the process variable x_i is utilised by the t^{th} test for the generation of diagnostic signal s_j. This relation comes directly from the structure of the diagnostic test. This relation can be expressed in the form of sub-relations which are more friendly to define and manage during the diagnostic system configuration and further exploitation [4]. These are the relations between: calculated variables and variables used in calculations, models and variables used as their inputs, models and its outputs, etc.

- Relation R^{SF} defined on the Cartesian product of the sets S and F:

$$R^{SF} \subset S \times F. \quad (5)$$

This relation is a set of pairs $<s_j,f_k>$, such that the signal s_j is sensitive to the fault f_k, i.e., it has an ability to detect that fault. This relation can be sometimes determined based on a mathematical description of diagnostic test algorithms that takes into account the influence of faults. It can be also formulated based on the expert knowledge. This process is also not simple and usually many uncertainties must be taken into account.

Basic process and diagnostic system description does not include any direct information about the **process structure**. The description of the process can be extended by the introduction of the information about the process **technological components** and their **connections** with the process and the diagnostic system components. New elements will allow us to define the diagnostic relation (5) in a different way that takes into account the process structure.

Let us introduce the following additional components to the diagnostic system description:

- The set of technological apparatus (components):

$$C = \{c_n : n = 1,2,\ldots,N\}. \quad (6)$$

- Relation $R^{FC,f}$ defined on the Cartesian product of the sets F and C:

$$R^{FC,f} \subset F \times C. \quad (7)$$

Expression $<f_k,c_n> \in R^{FC,f}$ denotes that the fault f_k influences the operation of a technological component c_n, i.e., it affects its behaviour.

- Relation $R^{CX,f}$ defined on the Cartesian product of the sets X and C:

$$R^{CX,f} \subset C \times X. \quad (8)$$

Expression $<c_n,x_i> \in R^{CX,f}$ denotes that the fault of the component c_n affects the value of the process variable x_i, related variable has "improper values", e.g., faulty measurement device produce wrong indications. The "improper values" causes observable symptoms for all the diagnostic tests that utilize this variable.

- Relation R^{SC} defined on the Cartesian product of the sets C and S:

$$R^{CS,f} \subset S \times C. \quad (9)$$

Expression $<s_j,c_n> \in R^{SC,f}$ denotes that the diagnostic test s_j detects the faults of the component c_n. This relation can also be expressed in the form of sub-relations which are more friendly to define and manage during the diagnostic system configuration and further exploitation [4], e.g., one can use the relation between models and modelled components. The use of relation (8) is optional because it can be written down as a part of relation (9). The use of the relation (8) depends on the user preferences.

- Relation $R^{CC,f}$ defined on the Cartesian product of the sets C and C:

$$R^{CC,f} \subset C \times C. \quad (10)$$

Expression $<c_m,c_n> \in R^{CC,f}$ denotes that the fault of component c_m affects the behaviour of the component c_n, i.e., it starts to behave in an abnormal manner. This relation defines the fault propagation rules between the technological components.

Relations (7) and (8) result directly from the structure of the process, and can be easily defined by the diagnostic system designer. Relations (9) and (10) are typically defined based on the expert knowledge about the model structure and the process with its physical and chemical dependences. They are the most difficult to define and, very often, are related with a strong uncertainty. To be able to take it into account, it is possible to use fuzzy relation instead of a classical one.

The above presented description can be extended with a relation defining the **hierarchical structure of the process components**. Such a structure corresponds to the technological division of the installation onto particular sections, technological apparatus, etc. It performs mainly ordering task. It is not directly used in the process of determining the diagnostic relation. However, it can be used in the process of the diagnostic system decomposition [4]. This issue exceeds the scope of this paper.

3. Diagnostic relation determination

The basic form of a diagnostic relation (5) can be reconstructed based on relations between process components and diagnostic system elements presented in Paragraph 2. It is possible to determine the preliminary binary diagnostic matrix (BDM) this way. This matrix shows a potential dependence (influence) between faults F and diagnostic signals S.

3.1. Fault propagation paths

Determination of the BDM is conducted by propagation of faults consequences through particular nodes of the process and diagnostic system component structure to the nodes representing diagnostic signals. Such "fault propagation paths" are created by composing two or more basic relations described in the previous paragraph. The following propagation paths ($F \rightarrow S$) are defined below.

- Direct or indirect influence $F \rightarrow S$ through the process variables:

$$f_k \xrightarrow{R^{FC,f}} c_m \left[\xrightarrow{R^{CC,f}} c_n \right] \xrightarrow{R^{CX,f}} x_i \xrightarrow{R^{XS}} s_j \quad (11)$$

The algorithm calculating the diagnostic signal s_j utilises particular process variables in computations that have "improper" values due to a faulty component. The optional connection of several interconnected technological components can appear in the path.

This path can also directly include used models if such elements are considered in the structure of in computations diagnostic system (thus detailed specifications of possible relations are beyond the scope of this paper).

- Direct influence $F \rightarrow S$ through indication of the scope of process being checked by the particular diagnostic test:

$$f_k \xrightarrow{R^{FC,f}} c_m \left[\xrightarrow{R^{CC,f}} c_n \right] \xrightarrow{R^{CS,f}} s_j \quad (12)$$

The algorithm of a diagnostic test producing the diagnostic signal s_j monitors the state of a faulty component (or a component with faulty behaviour due to faults present in connected components).

3.2. Generalised form of the diagnostic relation

The diagnostics relation in the form (5) does not take into account the system structure, however, it is indirectly related to its components. The **generalised form of the diagnostic relation** $\boldsymbol{R^{SF,G}}$ is introduced to directly show the connections of faults F and diagnostic signals S with the process components C. This relation is defined by two sub-relations: generalised relation R^{FC} and generalised relation R^{CS}.

Before defining the above relations one must notice that the fault f_k can indirectly influence the behaviour of the technological component c_m. Let us introduce the generalised relation $R^{CC,f}$ defined on the Cartesian product of the sets C and C:

$$R^{CC,f} \subset C \times C \,. \tag{13}$$

Expression $<c_m,c_n>\in R^{CC,f}$ denotes that there exists the path in the digraph representing the relation $R^{CC,f}$ between the component c_n and the component c_m.

Relation R^{FC} is defined on the Cartesian product of the sets F and C:

$$R^{FC} \subset F \times C \tag{14}$$

while expression $<f_k,c_n>\in R^{FC}$ denotes that the fault f_k influences the operation of the component c_n directly according to relation (7) or indirectly according to the existing path between technological components. The elements of the relation matrix R^{FC} are defined as:

$$\begin{aligned} &\langle f_k, c_n \rangle \in R^{FC} \Leftrightarrow \langle f_k, c_n \rangle \in R^{FC,f} \\ &\vee \exists_m \left(\langle f_k, c_m \rangle \in R^{FC,f} \wedge \langle c_m, c_n \rangle \in R^{CC,g} \right) \end{aligned} \tag{15}$$

Relation R^{CS} is defined on the Cartesian product of the sets C and S:

$$R^{CS} \subset C \times S \tag{16}$$

while expression $<c_n,s_j>\in R^{CS}$ denotes that the diagnostic test s_j detects the faults of the component c_n. The elements in the relation matrix R^{CS} are defined as:

$$\begin{aligned} &\langle c_n, s_j \rangle \in R^{CS} \Leftrightarrow \exists_i \left(\langle c_n, x_i \rangle \in R^{CX,f} \wedge \langle x_i, s_j \rangle \in R^{XS} \right) \\ &\vee \langle s_j, c_n \rangle \in R^{SC,f} \end{aligned} \tag{17}$$

Taking into account the relations (14) and (15), one can define the elements of the diagnostic matrix $R^{SF,g}$ as:

$$\langle s_j, f_k \rangle \in R^{SF,g} \Leftrightarrow \exists_n \left(\langle f_k, c_n \rangle \in R^{FC} \wedge \langle c_n, s_j \rangle \in R^{CS} \right) \tag{18}$$

4. Test application

The presented approach to the diagnostic relation determination was tested with the use of the laboratory setup in the Institute of Automatic Control and Robotics, Warsaw University of Technology. This setup represents a simple boiler system. The availability of the test installation made it possible to compare the determined diagnostic relation based on defined sub relations with the real one, observed during physical tests. The tested system consists of the tank, control-valve and water supply system. The system realises the control process of the water level in the horizontal tank. There are available approximately 10 process variables. There were defined 14 possible faults (actuator, measurement path and component faults) which were diagnosed with the use of 10 diagnostic tests (diagnostic signals). Achieved BDM matrices based on the expert knowledge and active experiments are shown in Fig. 2. Almost all elements of the pattern diagnostic matrix given by the expert were found out, however, some mistakes were done. Three elements of the relation were attributed erroneously: $\{f_{10}, s_1\}$, $\{f_{12}, s_1\}$ and $\{f_3, s_6\}$. Four elements of the relation hadn't been found: $\{f_7, s_2\}$, $\{f_8, s_2\}$, $\{f_3, s_5\}$ and $\{f_4, s_5\}$. Two elements, $\{f_9, s_8\}$ and $\{f_{10}, s_7\}$, had been pointed out during analysis but were omitted by the expert. The thorough analysis confirmed the expert mistakes: the missing elements should be added. The process of determining the diagnostic relation is not easy and connected with many uncertainties. It is the main reason of the mistakes that were found during the experiment. This situation can be "controlled" by introducing fuzzy relations between the process and the diagnostic system components. Such a relation would allow us to directly take into account the experts uncertainty. It would be a subject of further research.

R^{FS}	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}	f_{11}	f_{12}	f_{13}	f_{14}
s_1							1	1		1x		1x	1	1
s_2			1	1					1	1		1		1
s_3				1									1	
s_4						1			1	1		1	1	
s_5							1	1	1	1		1	1	
s_6	1	1	1x	1	1								1	
s_7										1	1			
s_8						1			1	1	1			
s_9										1				
S_{10}						1			1	1		1	1	

(grey)	Elements of the BDM defined by the expert and confirmed in the experiment
(grey, framed)	Elements of the BDM omitted by the expert but confirmed in the experiment
1	Elements of the BDM automatically determined based of defined sub-relations
x	Incorrectly attributed element during the automatic BDM determination

Fig. 2. Designed and achieved diagnostic matrix for the BOILER system
Rys. 2. Zaprojektowana i rzeczywista macierz diagnostyczna dla BOILER

5. Conclusion

The proposed set of relations allows us to write down a wide range of information about existing connections between the process and the diagnostic system components. The methodology is simple and easy and intuitive in application. However, one must remember that this description is not complete and unique. The achieved final result strongly depends on the designer knowledge and his carefulness.

The automatically generated, based on proposed relations, preliminary binary diagnostic matrix (BPDM) is a starting point toward creating the proper diagnostic relation. Such a matrix was called "preliminary" because it defines only the potential dependences between faults and diagnostic test results (observed symptoms). Its quality depends on the accuracy of defining the elementary relations. There exists a need for a careful verification of the achieved relation which should be done by the expert before the diagnostic system is started. Additionally, in the following steps, the relation described by the BPDM can be corrected and complemented based on the expert knowledge as well as gained experience, e.g., a typical step is the introduction of multi-valued evaluation of residuals that allows us to increase the fault distinguishability.

6. References

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