Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

Diagnostics of Industrial Processes in Decentralised Structures with Application of Fuzzy Logic

Jan M. Kościelny*, Michał Bartyś**
Michał Syfert***

*Warsaw University of Technology, Institute of Automatic Control and Robotics
Warsaw, Poland, (Tel: +48 22 84234380; e-mail: jmk@ mchtr.pw.edu.pl),
** Warsaw University of Technology, Institute of Automatic Control and Robotics
Warsaw, Poland, (e-mail: bartys@mchtr.pw.edu.pl),
*** Warsaw University of Technology, Institute of Automatic Control and Robotics
Warsaw, Poland, (e-mail: msyfert@mchtr.pw.edu.pl)

Abstract: In the paper the problem of decomposition of the diagnostic system has been described. Principles of diagnostics in the decentralised hierarchic structure with the application of fuzzy logic have been given. The features and advantages of diagnostics of industrial processes in decentralised structures have been discussed. An industrial example of diagnostic reasoning in the decomposed structure has been presented.

1. INTRODUCTION

The structures of contemporary control systems are functionally decentralised. Moreover, physical structures of these systems are geographically dislocated. It is obvious and natural, that diagnostic functions of decentralised system should be also carried out in decentralised structures. When developing diagnostic system for complex system, it is, in general, impossible to decompose the system into completely independent (uncoupled) diagnostic subsystems. This means, that symptoms of the faults that have been appeared in the particular subsystem may be also observed in other subsystems. The diagnostic algorithms in decentralised systems should take this problem into consideration. The principals of the diagnostics of the complex systems have been presented among others by (Chen and Patton, 1999; Gertler, 1998; Frank, 1990; Patton et. al., 1989, 2000; Kościelny, 1998; Korbicz et al., 2004).

In the paper the principles of fuzzy reasoning about faults in bi-level decentralised structures have been formulated. Reasoning algorithms presented in the paper can be assumed as extensions of the algorithms presented by (Kościelny, 1998; Korbicz *et al*., 2004) that have been based on Boolean logic. These algorithms have been developed for diagnostics of industrial processes in single and multiple-level hierarchic structures.

In the paper a new method of system decentralisation (partitioning) have been presented. Kościelny (1998) has been assumed that the subsets of detection algorithms and considered faults are disjunctive in the lower level subsystems. Simultaneously, the faults which symptoms appear in more then one subsystem of lower level are isolated on the higher level of diagnostic system. In contrast to this, in this paper, there have been assumed that subsets of detection algorithms carried out by the particular diagnostic systems are disjunctive but the sets of faults in the lower level of the diagnostic system must not be disjunctive. Additionally, there one has been assumed, that subsystems of the lower level of diagnostic system will carry out the diagnostic tasks locally without taking carry on the symptoms that appear in the other subsystems. Raw (primary) diagnoses obtained in the lower level are refined in the higher level by considering diagnoses obtained in all other subsystems of the lower level.

An advanced observer-based scheme was proposed by Ding and Zhang, (2006), for the design of a two-level monitoring system for distributed networked control systems. For each subsystem, an observer-based local FD unit is embedded, which only makes use of local control input and measured output signals.

Paper is structured as follows: In Section 2 the concept of bi-level hierarchic structure of decentralised diagnostic has been presented. The diagnostic principles in the first level have been given in Section 3 and the diagnostic principles in the second level have been given in Section 4. In Section 5 an example of decentralised diagnostics with application of fuzzy logic of steam-water line of power boiler has been given. Final remarks have been given at the end of the paper.

2. DECOMPOSITION OF CONTROL SYSTEM

A fault isolation system is defined by:

- the set of possible faults - F, assumed as a destructive events lowering quality factors of the whole system or its part:

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

- the set of diagnostic signals – S, considered as the outputs of the detection algorithms that are applied in the diagnostic system:

$$S = \{ s_j : j = 1,2,...,J \},\tag{2}$$

- diagnostic relation defined on the Cartesian product of the sets S and F

$$R \subset F \times S.\tag{3}$$

Expression $<f_k, s_j> \in R$ denotes that diagnostic signal s_j points out fault f_k i.e. appearance of fault f_k is associated with appearance of specific diagnostic signal s_j with assigned value 1. This specific diagnostic signal is called fault symptom. Relation matrix $\boldsymbol{R}$ forms a binary diagnostic matrix. Each element r_{kj} of matrix $\boldsymbol{R}$ is defined as follows:

$$r_{kj} = \begin{cases} 0 \Leftrightarrow \langle f_k, s_j \rangle \notin R \\ 1 \Leftrightarrow \langle f_k, s_j \rangle \in R. \end{cases}\tag{4}$$

Value of the particular diagnostic signal s_j in case of appearance of fault f_k is a reference diagnostic value and will be denoted as v_{kj}. Relation $\boldsymbol{R}$ may be rewritten in the form of the set of reasoning rules of following structure:

$$IF(s_1 = r_{k1}) and ... and (s_J = r_{kJ}) THEN\ f_k\tag{5}$$

For the system normal state (OK) holds:

$$IF(s_1 = 0) and ... and (s_J = 0) THEN\ state\ OK\tag{6}$$

Decomposition of the diagnosed system into a set of subsystems is necessary to carry out diagnostic tasks in decentralis~~z~~ed structures. For simplicity, assume that particular subsystems will be associated with separate technological apparatus or devices. Moreover, assume that decomposition is carried out in such a manner that holds following conditions:

- Subsets of diagnostic signals in subsystems of the first level are disjunctive:

$$S_m \cap S_n = \varnothing; \qquad m \neq n;\ m,n = 1,2,...N.\tag{7}$$

- Subsets of isolated faults in all subsystems of the first level are disjunctive:

$$F_m \cap F_n = \varnothing; \qquad m \neq n;\ m,n = 1,2,...N.\tag{8}$$

where: F_n is subset of faults pointed out in n-th subsystem by diagnostic signal s_j

$$F_n = \bigcup_{s_j \in S_n} F(s_j)\tag{9}$$

and $F(s_j)$ is a subset of faults pointed out in n-th subsystem by diagnostic signal s_j:

$$F(s_j) = \{ f_k :< f_k, s_j > \in R \}.\tag{10}$$

- Subrelations R_n of relation R are disjunctive:

$$R_n = F_n \times S_n \subset R.\tag{11}$$

- On the higher level of diagnostic system are carried out detection algorithms sensitive to the faults originating from minimum two subsystems. Therefore, a subsets of faults F^2 isolated in the higher level system and in the subsystems of the first level are not disjunctive in general:

$$F^2 \cap F_n \neq \varnothing; \qquad n = 1,2,...,N.\tag{12}$$

- Subset of detection algorithms carried out on the higher (master) level is disjunctive with the all subsets of detection algorithms from the first level. Therefore, a subset of diagnostic signals S^2 carried out on the higher level is disjunctive with the all subsets of diagnostic signals on the first level. Hence, subsets of generated subsets of diagnostic signals are also disjunctive:

$$S^2 \cap S_n = \varnothing; \qquad n = 1, 2, ..., N.\tag{13}$$

The set of faults simultaneously detectable in the higher level and in the n-th subsystem of the first level is following:

$$F_n^2 = \{ f_k \in F^2 \cap F_n \},\tag{14}$$

where:

$$F^2 = \bigcup_{s_j \in S^2} F(s_j).\tag{15}$$

Each subsystem of the first level is defined as the following triplet:

$$O_n =< F_n, S_n, R_n >.\tag{16}$$

Diagnostic relation in the higher level system R^2 is a subset ot the diagnostic relation $\boldsymbol{R}$ of the system:

$$R^2 = F^2 \times S^2 \subset R.\tag{17}$$

Master subsystem (subsystem of the higher level) is defined by the following triplet:

$$O^2 =< F^2, S^2, R^2 >.\tag{18}$$

Block diagram of the hierarchic two-level structure of the diagnostic system have been presented on Fig.1.

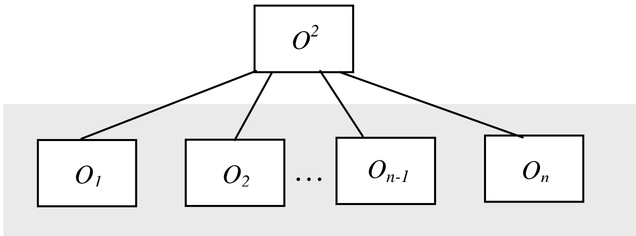

Fig.1. Block schematics of bi-level hierarchic structure of the decentralised diagnostic system

3. DIAGNOSTICS IN SUBSYSTEMS OF THE FIRST LEVEL

Assume, that each of the subsystems of the first level is directly associated with the diagnosed objects. Diagnostics in the subsystems is based on partial models of the diagnosed systems. Having these models, a set of residuals Res_n is generated in each n-th subsystem. Evaluation of the set of residuals allow to obtain the set of diagnostic signals S_n. Constant or adaptive bi-valued residual threshold evaluation techniques possess many substantial drawbacks. The residual evaluation based on the threshold passing tests may fail particular in case of uncertain signals, and in consequence may induce contradictory conclusions or false diagnosis. Application of fuzzy logic may be useful to overcome the diagnosis "flickering effects" in case of uncertain diagnostic signals. The main idea is based on the introduction of fuzzy residual threshold - thus softening the diagnostic decision transitions from faultless to faulty states. The residual evaluation is defined as the operation that maps the residual space into the fuzzy fault symptom space.

Let each residual r_j will be associated with the linguistic variable V_j defining values of the diagnostic signal in the form of fuzzy sets. Further, let space of discourse of linguistic variable V_j will be identical with the set of residual values r_j. Take for example the simplest case of bi-valued fuzzy evaluation of residuals. Here, the linguistic variable V_j is also bi-valued, although V_j values are rather fuzzy sets then crisp values. In this example variable V_j may have two values (fuzzy sets) $V_j=\{0,1\}$ denoted for example as 0 and 1 and interpreted appropriately as an absence and presence of a fault symptom. Hence, membership functions of values of linguistic variable V_j define fuzzy diagnostic values:

$$s_j = \{< \mu_{ji}, v_{ji}, >: v_{ji} \in V_j\} = \{< \mu_{j0}, 0 >, < \mu_{j1}, 1 >\}, \tag{19}$$

where: μ_{ji} – membership of j-th residual to i-th fuzzy set v_{ji}.

Fuzzyfied diagnostic signals are inputs to the rule based inference machine. Inference about faults is based on Mamdani's implication scheme and assumption about appearance of single faults. Number of outputs of this machine equals K_n+1, where K_n is a number of faults detectable in the n-th subsystem. K_n+1-*th* output is assigned to the normal state (OK) of the subsystem. Here, activation level of each K_n+1 rule is assumed as fault existence coefficient. Values of these coefficients vary in the range [0, 1].

Degree of fulfilment of primary premises for the *j-th* diagnostic signal in *k-th* rule $\mu(f_k,s_j)$ depends on the conformity of the obtained *j-th* diagnostic signal value with its reference value depicted in the *k-th* rule. Degree of activation of the rule about *k-th* fault is given in the form of conjunction of simple premises:

$$\mu(f_k) = \mu(f_k, s_1) \otimes \mu(f_k, s_2) \otimes \ldots \otimes \mu(f_k, s_J), \tag{20}$$

where: $\otimes$ - general operator of fuzzy conjunction

The rule of the OK state is as folows:

$$\mu(OK) = \mu(s_1 = 0) \otimes \mu(s_2 = 0) \otimes \ldots \otimes \mu(s_J = 0) \tag{21}$$

Each rule generates fuzzy conclusion about one fault. Conclusions of the rules may not be disjunctive what means that rules are contradictory. Faults are indistinguishable (Gertler, 1998; Korbicz *et al*., 2004) in case if different rules by given set of premises generate different faults.

Degrees of activation of the rules (20) are typically calculated by means of T-norm operators e.g. PROD or MIN operator. PROD operator is defined as arithmetic product of the degrees of fulfilment of all simple premises in the rule:

$$\mu(f_k)_{PROD} = \mu(f_k, s_1) \cdot \mu(f_k, s_2) \cdot \ldots \cdot \mu(f_k, s_J) \ , \tag{22}$$

where: $(\cdot)$ operator of arithmetic product.

Operator MIN is defined as an intersection of fuzzy sets:

$$\mu(f_k)_{MIN} = \min\{\mu(f_k, s_1), \mu(f_k, s_2), \ldots, \mu(f_k, s_J)\ \} \ . \tag{23}$$

Activation levels of rules (5) are interpreted as certainty degrees of particular faults. Activation level of the rule (6) is interpreted as the certainty degree of fault absence. This constitutes the raw (introductory) fuzzy diagnosis produced on the output of the fuzzy fault isolation system. The diagnosis is a fuzzy set consisting of set of pairs: fault, fault certainty degree. Formally, fault certainty degrees are identical with membership degrees of fuzzy diagnosis.

$$DGN_n^* = \{< \mu(OK_n), OK_n >\} \cup \{< \mu(f_k), f_k >: \mu(f_k) > 0\} \tag{24}$$
$$for\ k = 0, 1, \ldots, K_n$$

Define the set of faults F_n^I detectable exclusively in given n-th subsystem:

$$F_n^I = F_n - F_n^2, \tag{25}$$

where: F_n^2 is defined by (14).

Diagnosis (24) one may interpret as a union of two sets of faults, where first set (called internal) contains exclusively the faults detected in the considered subsystem. The second subset (called external) contains faults detected in the n-th subsystem and in minimum one subsystem of the first level or in master level.

$$\begin{aligned} DGN_n^* = &\{< \mu(OK_n) >\} \cup \{< \mu(f_i)_n, f_i >: f_i \in F_n^I\} \\ &\cup \{< \mu(f_k)_n, f_k >: f_k \in F_n^2\} \end{aligned} \tag{26}$$

If all faults pointed out in raw diagnosis DGN_n^* belong to the set F_n^I then final diagnosis DGN_n is identical with DGN_n^*. This diagnosis cannot be tuned or verified on the master level based on the primary diagnoses generated in remaining subsystems. However, diagnosis can be tuned or verified if primary diagnosis contains faults belonging to the subset F_n^2.

The first stage of the diagnostics in the master level is realised identically to the diagnostics process in the subsystems of the first level. Second stage of reasoning on the master level is aimed on refining of diagnoses elaborated in all subsystems of the first level and in the master level. This stage of diagnosis is necessary if and only if diagnoses point out faults belonging to the sets F_n^2 of faults detected by the particular pairs of subsystems.

4. REFINING OF THE RAW DIAGNOSES

Following tasks are carried out by master level of diagnostic system:

- generation of local raw diagnosis DGN^{2*} based on the detection algorithms carried out on the master level,
- refining of local diagnosis generated in the subsystems of the first level based on the diagnoses generated by the master level,
- formulation of the final diagnosis.

Raw diagnoses generated in the subsystems of the first level are consisting from two parts (26). First part of the diagnosis deals exclusively with the faults detectable within given subsystem, while the second part deals with the faults determined commonly in the considered subsystem and on the master level. If raw diagnoses elaborated in the subsystems of the first level contain this second part then there is possible to refine this diagnosis based on the diagnosis from the master level. This refinement deals only with the *external* part of diagnosis DGN_n^*. The reasoning rule about this fault have a form of conjunction of premises of all rules valid for this fault in both subsystems.

$$f_k \in F_n^2 \Rightarrow \mu(f_k)_n^2 = \mu(f_k)_n \otimes \mu(f_k)^2 \tag{27}$$

Possible are two following cases:

- Raw diagnosis in the master level does not contain fault $f_k \in F_n^2$ pointed out in diagnosis DGN_n^* on the first level. This means, that $\mu(f_k)^2=0$ and according to (26) such faults are rejected from the final diagnosis of the n-th subsystem. Then assuming single faults one should remove them from the diagnosis of the n-th subsystem DGN_n:

$$\begin{aligned} &[\, f_k \in F_n^2 \,] \wedge [< f_k, \mu(f_k)_n > \in DGN_n^* \,] \\ &\wedge [< f_k, \mu(f_k)^2 > \notin DGN^{2*} \,] \Rightarrow \\ &\mu(f_k)^2 = 0 \wedge < f_k, \mu(f_k)_n^2 > \notin DGN_n \end{aligned} \tag{28}$$

- Raw diagnosis from the master level contains fault $f_k \in F_n^2$ pointed out in diagnosis DGN_n^*. Degree of activation of the rule about this fault is calculated in this case, according to (27). Because value of this degree is different from zero, then this fault is pointed out in final diagnosis of n-th subsystem DGN_n^2 of the first level:

$$\begin{aligned} &[\, f_k \in F_n^2 \,] \wedge [< f_k, \mu(f_k)_n > \in DGN_n^* \,] \\ &\wedge [< f_k, \mu(f_k)^2 > \in DGN^{2*} \,] \Rightarrow \\ &< f_k, \mu(f_k)_n^2 > \in DGN_n \wedge < f_k, \mu(f_k)_n^2 > \in DGN^2 \end{aligned} \tag{30}$$

Refining of the diagnoses in particular subsystems of the first and master levels are carried out according to the given above principles of reasoning.

5. EXAMPLE

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. This installation in main part is build-in the power boiler and is hidden for the external observer. 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.2. 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 accurately due to optimisation demands of the watt-hour efficiency. Too high steam temperature may cause accelerated wear or even damage of the elements of steam-water line or turbine blades. The steam temperature is lowered by injection of cool water into the steam flow. The steam attemperator assembly is used for this purpose. The throttling valve of 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 were given. Exclusively abrupt faults have been considered. 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 Tab. 1. This table illustrates the decomposition of the system. Double, vertical line separates two subsets of faults of the left and right steam-water lines. 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. These signals are generated by the detection algorithms on the master level. Two subsequent subsets of diagnostic signals are responding to the subsystems of the first level. It is easy to see, that for subsystems of the first level, the sets of detected signals are disjunctive. Decomposition of the system meets assumptions given in Section 2.

Particular subsystems are defined by the subsets of faults, diagnostic signals and diagnostic relation being a subset of the relation $\boldsymbol{R}$:

- Subsystem $O_1 = < F_1, S_1, R_1 >$, where:

$F_1 = \{f_1 - f_{23}\}$ and $\{ f_k - f_m \}$ denotes set of all faults with indices from k to m.

$S_1 = \{s_{10} - s_{22}\}$

- Subsystem $O_2 = < F_2, S_2, R_2 >$, where:

$F_2 = \{ f_{24} - f_{45} \}$

$S_2 = \{ s_{23} - s_{35} \}$

- Subsystem $O^2 = < F^2, S^2, R^2 >$, where:

$F^2 = \{f_2 - f_4, f_{13}, f_{18}, f_{21}, f_{22}, f_{24} - f_{26}, f_{35}, f_{40}, f_{43}, f_{44}\}$

$S^2 = \{s_1 - s_9\}$

Consider following values of diagnostic signals in particular subsystems:

- *Subsystem O_1:*
  $s_{15}=\{<0,0.10>,<1,0.90>\}$, $s_{18}=\{<0,0.10>,<1,0.90>\}$ and all remaining values of diagnostic signals: $s_i=\{<0,1>,<1,0>\}$.
- *Subsystem O_2:*
  Only one symptom was registered: $s_{26}=\{<0,0.05>,<1,0.95>\}$ and all remaining values of diagnostic signals: $s_i=\{<0,1>,<1,0>\}$.
- *Master subsystem O^2:*
  Two symptoms were registered $s_6=\{<0,0.20>,<1,0.80>\}$, $s_9=\{<0,0.10>,<1,0.90>\}$, and all remaining values of diagnostic signals: $s_i=\{<0,1>,<1,0>\}$.

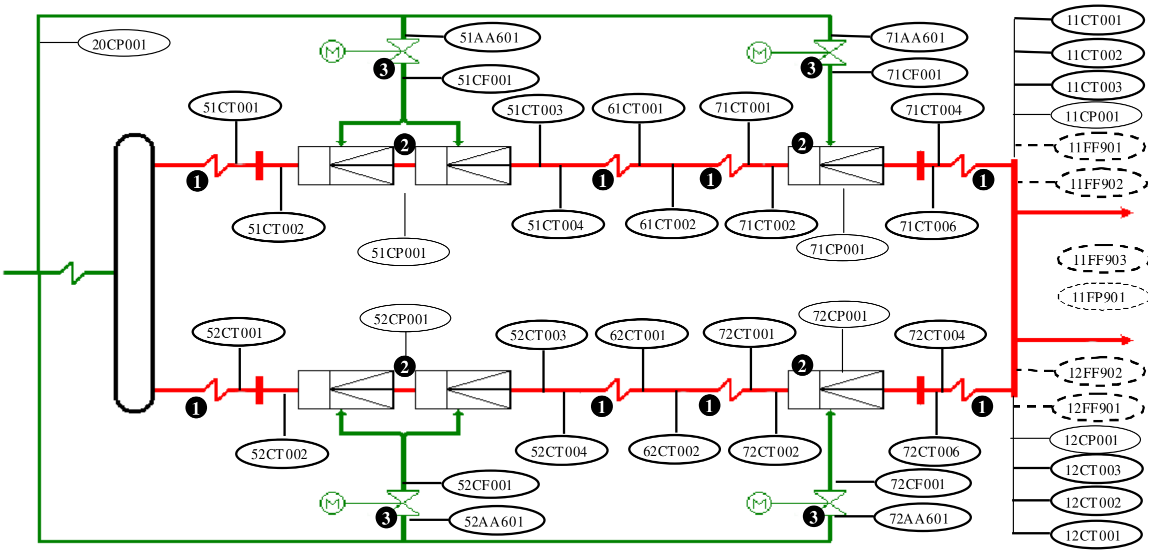

Fig. 2. Diagram of steam-water line of boiler of power station

FS	f01	f02	f03	f04	f05	f06	f07	f08	f09	f10	f11	f12	f13	f14	f15	f16	f17	f18	f19	f20	f21	f22	f23
S01		1																					
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FS	f24	f25	f26	f27	f28	f29	f30	f31	f32	f33	f34	f35	f36	f37	f38	f39	f40	f41	f42	f43	f44	f45
S01	1																					
S02		1																				
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S35																					1	1

Tab.1. Binary diagnostic matrix of steam-water line of power boiler. Black shaded areas represent Boolean values equal 1.

MIN operator was applied for fuzzy reasoning. Following primary diagnoses have been generated in both subsystems in accordance with inference rules given in Section 3.

$$DGN_1^* = \{ < 0.10, OK_1 > \} \cup \{ < f_{11}, 0.90 > \},$$

$$DGN_2^* = \{ < 0.05, OK_2 > \} \cup \{ < f_{43}, 0.95 > \},$$

$$DGN^{2*} = \{ < 0.20, OK^2 > \} \cup \{ < f_{21}, 0.80 >, < f_{43}, 0.80 > \}.$$

In respect to given inference rules final diagnosis are as follows:

$$DGN_1 = \{ < 0.10, OK_1 > \} \cup \{ < f_{11}, 0.90 > \},$$

$$DGN_2^* = \{ < 0.05, OK_2 > \} \cup \{ < f_{43}, 0.80 > \},$$

$$DGN^{2*} = \{ < 0.20, OK^2 > \} \cup \{ < f_{43}, 0.80 > \}.$$

6. FINAL REMARKS

In the paper the principles of the novel diagnostic reasoning about faults in hierarchical decentralised bi-level structure have been presented. It have been shown on example of steam-water line of power boiler, that diagnostics in decentralised structures make possible isolation of multiple faults even in case if reasoning about faults is carried out with assumption about single faults. The difficulties in formulation of regular diagnosis will appear only if multiple faults will exist only in the one subsystem or in the set of faults detected simultaneously in two subsystems. In these cases, the inference principles taking into account system states with multiple faults (Kościelny, 1998; Korbicz *et al.*, 2004) should be taken into account. Practical algorithms of isolation of multiple faults have been also described in Kościelny *et al.*, 2006.

System partitioning driven by the process components raises the problem of dealing with the faults that affect more then one component. In this case it is reasonable to arrange partitioning of components in such a manner that it will minimise the effects of multilateral coupling of subsystems. This problem was solved by means of system decomposition with application of genetic optimisation algorithms (Wnuk *et al.*, 2007).

Decentralised diagnostics allow to accommodate and shape structure of the diagnostic system according to the decentralised structure of the existing industrial control systems. This allows taking advantages from possibility of parallel processing of process data for diagnostic purposes. Fuzzy reasoning about faults, in contrast to the reasoning based on Boolean logic, gives the opportunity to comply with symptom uncertainties and gives some immune against appearing of improper diagnoses in case of false selection of thresholds of the residuals.

ACKNOWLEDGEMENTS

The authors acknowledge funding support of Polish Ministry of Education and Higher Education under the grant R01 012 02 DIASTER: *Intelligent diagnostic system supporting control of industrial processes*. Project financed from the fund supporting research in the years 2007-2009.

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