MODEL-BASED FAULT DIAGNOSIS IN A WASTE-PROCESSING INDUSTRIAL SYSTEM VIA CAUSAL GRAPHS

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Abstract. The paper describes a Casual Graph (CAG) approach to fault diagnosis of industrial systems, based on logical and qualitative methodology for modelling the diagnostic aspects of a system structure and behaviour. The main goal consists in a development of necessary algorithmic structures, which are applied in an intelligent diagnostic system, based on a deep representation of the knowledge. A specific CAG diagnostic model, representing the causal behaviour of the diagnosed waste-processing industrial system is developed and presented in the paper. The diagnostic process is developed as a multi-stage algorithm, consisting of following main stages: failure detection, search for solutions, model tests, causal relations among symptoms and faults, and validation procedures.

Keywords: model-based fault diagnosis, causal graphs, knowledge representation, diagnostic reasoning, system's behaviour

1. Introduction

An enhanced analysis, performed over the existing diagnostic systems revealed, that, in general, three major diagnostic approaches, which are sufficiently developed and implemented under real operational conditions, (i.e., for fault diagnosis of industrial processes), could be named.

A). ***Heuristic Diagnostic Approach (HDA),*** where, *the industrial diagnostic system are developed and applied as **rule-based** expert systems* [3, 4, 6]. Such types of rule-based diagnostic systems implement the so-called "shallow" knowledge, provided by the experts (and known also as "*an experimental type*" *of knowledge*), during the evaluation and decision procedures, developed respectively in the system reasoning and decision-making algorithms [8, 10]. The expert knowledge about some possible symptoms of the system malfunctioning is encoded in the form of production rules [3, 4]. Some possible repair procedures can also be provided by the system modules, (if supplementary included in the system structure) [3, 4]. One of the issues, of the rule-based systems is their limited domain of expertise and application, since a diagnostic system, using an experimental (a shallow) knowledge can be used exclusively for diagnosis in a domain, which is described by the expert-provided rules. If, a rule-based diagnostic system meets an observation, which is not treated and included in the experimental data, then the diagnostic system could not perform its diagnostic task [2, 4].

B). ***Fault Detection and Isolation (FDI)*** approach, where, the developed diagnostic systems are based on analytical models of the industrial systems and/or processes, (subjected to fault diagnosis). Such diagnostic systems use parameter estimation methods for detecting the abnormal model outputs, and thus – identifying the components, that cause the observed system behavior. *This kind of diagnostic approach is referred as **Fault Detection and Isolation (FDI)*** [4, 7, 8]. The main issue of the ***FDI*** is that it can be successfully applied, only if adequate analytical model of the process/system under consideration can be developed [4].

C). ***Model-Based Diagnostic approach (MBD),*** known also as *"Diagnosis from First Principle (DFP)"* [5, 9]. The MBD approach use the *deep knowledge* for the ***Internal Structure*** and the ***Causal Behavior*** of the systems, for creation and application of the diagnostic models (rather than the shallow diagnostic knowledge, provided by the experts) [4, 9]. Such types of diagnostic systems are based exclusively on a ***deep knowledge***, and/or on ***combinations*** *between shallow and deep knowledge* [5, 8, 9]. A sufficiently complex reasoning algorithms, designated for fault determination and based on *deep knowledge* and *causal reasoning* about the system behavior should be developed and applied (a set of symptoms must also be available for the purpose) [7, 9].

The *main goal of this paper* is to develop algorithmic modelling structures, which could be applied in intelligent diagnostic systems, based on a deep representation of the knowledge.

A specific ***Causal Graph (CAG) model***, describing the causal behaviour of an industrial waste-processing system is developed and applied for the purpose.

The applied CAG approach to fault diagnosis is based on a logical and on qualitative methodology for modelling the diagnostic aspects of the system structure and behaviour.

2. Structure of the industrial waste-processing system, subjected to Fault Diagnosis (FD) Procedures

The industrial waste processing system (subjected to FD procedures) is included in the technologic and logistic structures, developed for a Hot Dip Zinc Galvanizing facility, under the financing program of the US Overseas Private Investment Corporation (OPIC).

All important details, regarding the system structures, the equipment characteristics, the logistics and the processing technologies of the Zinc Galvanizing Plant are developed and presented in [1] and [2].

The developed industrial waste-processing system, comprise a ***waste liquids treatment equipment*** and an ***air pollution control equipment***. The waste liquids treatment system is capable to treat the waste liquids from the plant pickle area and to maintain a proper chemistry in the process tanks.

The following processing modules are included in the structure of the waste liquids treatment system:

- *Filter Press for treatment of the waste liquids & sludge;*
- *Control System (CS);*
- *Level Sensors (LS);*
- *Central Pumping Station (P);*
- *Valve (V1) of the pumping station;*
- *Valve (V2) of the Filter press main frame;*
- *Tanks for waste liquids;*

The structure of the liquid waste-processing system, subjected to FD procedures is shown on Figure 1.

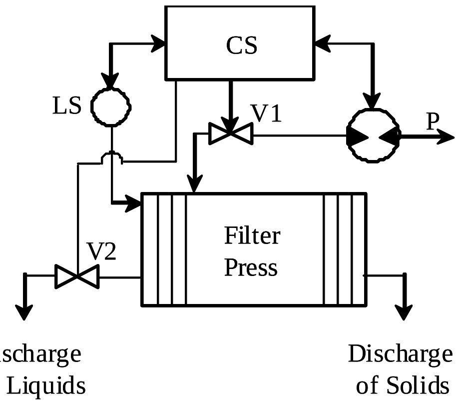

Figure 1. Structure of the liquid waste-processing system, subjected to FD procedures

The ***Filter Press*** (Figure 2) is used to remove the liquids from the sludge. The resulting press-cake (processed by the filtering diaphragms) appears as a semi-dry material (with about 30% solids and no free liquid), and is discharged as a solid material (i.e. solids), separately from the treated liquids.

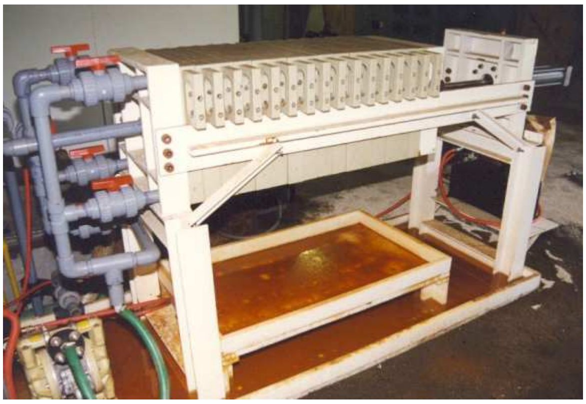

Figure 2. Filter Press for treatment of the waste liquids

The FD procedures were developed over the structural modules of the liquid waste-processing system. Several major events could be considered as an *abnormal behavior*, and could express the ***failures***, generated in the waste-processing system:

- failure F_1 – an overflow of the waste liquids (during the system processing cycle);
- failure F_2 – signal error in the LS;
- failure F_3 – malfunction in V1.

In case, one of these failures could be observed – then the FD procedures must be started. The developed FD are based on reasoning algorithms, which use diagnostic model, developed as a Causal Graph (CAG).

3. Development of a CAG-diagnostic model for the liquid waste-processing system

A particular kind of ***CAG diagnostic model***, which describes the *causal behaviour* of the industrial waste-processing system is developed and applied during the FD of this real industrial system. The CAG-model structure is shown on Figure 3.

The applied CAG approaches to FD use logical and qualitative methodology for modelling the structure and the behaviour of the industrial waste-processing system.

In fact, the developed reasoning algorithms are *rather complex*. They use G*enetic-type operators*, developed as ***Selection, Crossing-over and Mutation in Genetic type algorithms*** (which are not subject to this paper), for preliminary generation of adequate sets of diagnostic symptoms, as well as for logical and/or qualitative evaluation.

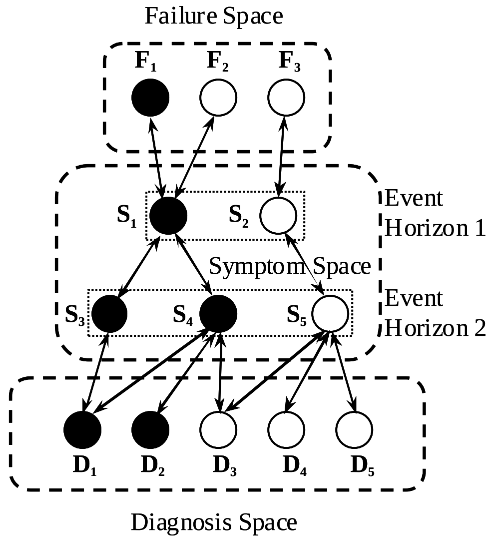

Figure 3. CAG diagnostic model of the industrial, liquid waste-processing system

All diagnostic symptoms (represented by the CAG nodes), which were find to be ***true*** *(by the* ***Genetic Reasoning Algorithms****) are marked with filled circles (in the model structure), while the symptoms, which were find to be* ***false****, were respectively marked with empty circles.*

The CAG diagnostic model is developed like a complex structure, composed of three different regions, named respectively ***"Diagnosis Space", "Symptom Space"*** *and* ***"Failure Space***". The connections (i.e., the arcs) in the CAG model structure can interact in both directions and provide options for development of the logical and/or qualitative algorithmic (i.e., reasoning) procedures also in both directions. The developed CAG model can then perform the analysis from symptoms to causes, but also can act vice-versa (i.e., from causes to symptoms), thus providing a ***fault-tolerance*** of the diagnostic reasoning and preventing the algorithmic failure in the FD procedures.

The *sets of symptoms* are structured in two layers, named "*event horizons*" and can provide the necessary "depth" of the reasoning and decision procedures. The symptom sets express the following causal events in this particular CAG:

- symptom S_1 –LS is blocked when open;
- symptom S_2 – V2 is not open;
- symptom S_3 – LS provides faulty signal signature;
- symptom S_4 – V1 is not responding;
- symptom S_5 – LS is blocked when closed.

The diagnosis sets express the ***possible initial causes***, which are in fact the ***diagnostic events***, generated by the CAG. These initial causes are named "*Diagnoses*" – $\mathbf{D_i}$, and represent respectively the following diagnostic events:

- diagnose D_1 – LS is in failure;
- diagnose D_2 – V1 is in failure;
- diagnose D_3 – P is "On" by control;
- diagnose D_4 – P is in fault;
- diagnose D_5 – V1 is stuck closed.

From the logical point of view, some of the "Symptom nodes", composing the event horizons in the developed CAG, could be referred also as an *"and-nodes"*, in cases, when they are built as a result of two or more ***true*** symptoms that are generated at the same time. The symptoms are so-called "*ancestors*" (or "parents") in the developed Genetic Operator. In this particular CAG these symptoms respectively are – S_1, S_4 and S_5. Of course the *true* and *false* reasoning is having the leading role, when performing this symptom evaluation. In the "and-nodes" cases, all ancestors' nodes were evaluated to be true. There exist also other types of symptom nodes, which could be referred as "*or–nodes*". In the "or-nodes" cases, at least one of the ancestor's symptoms was evaluated to be true in the CAG structure.

4. Causal relationships among symptoms and diagnoses in CAG - diagnostic model. Diagnostic reasoning

One of the most important issues that must resolve when analyzing the faulty behavior in technical systems (subjected to FD) is the determination of causal relationships among the symptoms.

Several major types (categories) of symptoms, which are included in the developed CAG-modeling structure could be selected, determined and applied in the analysis of the causal relations.

A). ***Failure symptoms*** (or just failures – F_i). These symptoms indicate an abnormal behavior of the diagnosed system(s). If a certain failure is detected and/or observed, then the FD process can be started. The sets of the considered failure symptoms (failures) are located in the Failure Space of the CAG structure and are denoted as: $\mathbf{\{F\} = \{F_1, F_2, ..., F_N\}}$. The main issue here, is that the failure symptoms could be applied during the *preventive diagnostic procedures*, since the F_i are not realized events, when developing a failure prevention of the diagnosed system.

B). ***Basic symptoms*** (referred also as an *initial cause symptoms*). A "basic symptom" represents a symptom, which is included in the core of the modeling structure, could emerge without any visible reason, and for which there is no necessity to search for any further cause for its generation. This is the most presentable set of symptoms that is determined by the genetic operators (in fact, they create the so-called "pool of the chosen symptoms"). Such symptom sets could be subdivided into three particular groups (sub-sets) of the following types:

- Sub-sets, composed of *System component faults* (S_C), denoted as: $\{S_C\} = \{S_{C1}, S_{C2}, ..., S_{CS}\}$;
- Sub-sets, composed of *Control actions* (C_A), and denoted as: $\{C_A\} = \{C_{A1}, C_{A2}, ..., C_{AC}\}$;
- Sub-sets, composed of *Environmental Operational Condition* (EO_C), and denoted as: $\{EO_C\} = \{EO_{C1}, EO_{C2}, ..., EO_{CM}\}$.

C). *Ambiguity symptoms – {AS}.* Such types of symptoms are neither faults, neither have they belonged to some of the sub-sets of basic symptoms. One of the most important groups of the ambiguity symptoms are included in the negative causal influence, generated in the developed CAG. This means, that in such cases, the presentable (i.e., the "justifying") symptom may take the form of a "negative presence", i.e., a confirmed lack of such a symptom is the main specific criteria for some particular system diagnose.

In fact, the developed CAG structure shows how, all types of symptoms could be applied for enhanced FD procedures. For example the event $\overline{D_3}$ (which is the supplementary event to $\mathbf{D_3}$), means in fact the negation of a symptom, i.e., "P is Off by control".

The CAG model provides options for several possible (i.e., potential) explanations of the diagnostic reasoning, when analyzing the faulty behavior of the system. Any diagnostic set, containing at least one element of $\{\mathbf{D_1}, \mathbf{D_2}, \mathbf{D_3}\}$ and at least one element of $\{\overline{D_3}, \mathbf{D_4}, \mathbf{D_5}\}$ could be considered as "possible" (*i.e.*, "potential") diagnose. The "minimal" diagnoses are presented by the so-called "minimal sets", (applied successfully in the system reliability evaluation) and respectively are: **{D1}**, **{D2}**, **{D1**, $\overline{D_3}$**}**, **{D2**, $\overline{D_3}$**}** and **{**$\overline{D_3}$**}**. It should be noted, that some of the possible diagnoses refer ***not only*** to some *faulty component*, but also to some combinations of *control actions*, and/or *operational conditions*.

In general for solving a FD problem it is necessary to develop a search procedure aiming a determination of some set, composed of initial cause symptoms, which can explain (i.e., "justify" the observed failures.

The search for possible diagnoses (it is not necessary that, they should be just the minimal ones), could be developed as a systematic search procedure, developed in the CAG model structure. Therefore, the diagnostic issue of finding a *possible diagnoses*, for a *determined set of failure symptoms* (defining some type(s) of abnormal system behavior), represents in fact an *equivalence* to *finding a set of basic symptoms*, (defining respectively the faulty components, the undertaken controls actions, and the analyzed external signals from the environmental operating conditions), with *respect to causal relations, defined by the CAG*.

5. Conclusions

5.1. A particular type of ***CAG diagnostic model***, which describes the *causal behaviour* of the industrial waste-processing system, is developed.

5.2. Causal relationships among symptoms and diagnoses, generated in the CAG-modeling structure are determined and applied during the development of Diagnostic reasoning procedures.

5.3. The created CAG-modeling structure and the defined FD reasoning procedures are then applied during the FD of an industrial liquid waste-processing system, under real operational conditions.

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