Abstract

This paper presents an approach for using process knowledge in addition to structural knowledge for plant-wide diagnosis. System diagnosis based on fault-detection and fault-diagnosis often uses structural knowledge (e.g. hierarchies of sub-systems and components) to identify the root cause of faults and malfunctions. The structural knowledge describes the internal relationships of a plant and is particularly suitable for diagnosis if an assembly or component breaks down, which affects other parts of the system. However, the root cause of faults cannot always be identified based on structural knowledge alone, but information about the processes (e.g. production processes) is required in addition. Based on an integration of the VDI/VDE-guideline 3682 “Formalized process description” the authors present a method to consider process knowledge for an improved system diagnosis.

1. Introduction

The aims of users of industrial systems are besides economical reasons like increasing availability, dependability and productivity by reducing downtime and failure. For this an observation of the process or plant with monitoring system [1] offers the possibility for an early fault-detection and fault-identification. Both, detection and identification are grouped into fault-diagnosis and are essential for the efficient operation of technical systems e.g. in the manufacturing or process industry. Hence, the field of fault diagnosis methods has been increased over the last years due to economical and safety related matters. Generally, fault diagnosis can be divided into two parts: fault-detection and fault-diagnosis. The goal of fault-detection methods is the identification of constitutional changes within a running system. The methods can be classified into different types of detections e.g. limit- and trend-checking, use of signal- and process-models or state estimation [2]. In most cases, the surveillance is based on quantitative methods to detect deviations of important values. The result of fault-detection methods is a fault or symptom which is detected at a component of the system, e.g. a sensor. The results of the fault-detection are the basis for the following methods of fault-diagnosis. The purpose of fault-diagnosis is to determine kind, size, location and time of detection of the fault or deviation [2]. As the methods of fault-detection and fault-diagnosis are not in the focus of the paper, this will not be discussed here in more detail. Further general approaches, techniques and methods are discussed in [2; 3; 4; 5; 6]. Fault diagnosis of discrete event systems is dealt with in [3; 7].

For the identification of the root cause of a fault, the system diagnosis needs to have knowledge about the system’s structure as well as the system’s components and their internal relationships, such as (i) product flow through a plant, (ii) energy flow between plant components, (iii) physical (mostly mechanical) connections of components and assemblies, and (iv) information flow between components. For a computer-based system diagnosis, this structural information must be available in a data format which can be stored and evaluated in computers. A suitable format to store structural and hierarchical system information is described in Section 2. Furthermore, the use of structural knowledge for diagnosis applications is explained by two examples, manufacturing and chemical, as well as the limitations of this approach in Section 3. A detailed definition, modeling and description of process knowledge and an enhanced diagnosis based on a process model is presented in Section 4.

2. The Use of Structural Knowledge in Diagnosis

2.1. Definition and description of structural knowledge

Structural knowledge describes the internal construction of a technical system, such as a production line in the manufacturing industry. The structural knowledge includes all components of a
system, e.g. machines, conveyor belts, pipes, sensors, actuators, etc. Components are described by different attributes like name, id, position and size. Furthermore, components must be linked with physical connections for transporting material or energy and electrical connections for power supply or communication. For the description of a modular system, single components are combined into units or assemblies. The result of the combination is a hierarchical structure of the system with the single components at the lowest level and the whole plant at the top.

For the storage of all data and information of a system, the object-oriented meta-model CAEX (Computer Aided Engineering eXchange) can be used. CAEX is specified in the standard IEC 62424. CAEX was developed for an interdisciplinary and neutral exchange of hierarchically described systems. For more detailed information on CAEX see [8].

Today, engineering of complex plants is based on the re-use of already-existing engineering solutions, such as modules and predefined assemblies, for cost-effective engineering. To include this in the system description, CAEX uses pre-defined classes, which are grouped in three different class libraries. The library concept defines: SystemUnitClass, RoleClass and InterfaceClass.

CAEX enables the interdisciplinary exchange of project-related engineering data and information. The existing engineering data is used during the plant life cycle. The standardized storage of data and information enables a seamless engineering chain with the possibility of a computer-based evaluation and further processing of this data. Different approaches using CAEX as a data base in the engineering process are published in [9, 10, 11].

In the following sub-section, the use of CAEX for the description of a discrete manufacturing line is explained.

2.2. Structural description of a discrete manufacturing line: an example

The use of CAEX for the hierarchical and object-oriented description of a discrete manufacturing system, including single components and assemblies, is demonstrated at the example of a manufacturing pilot plant. Fig. 1 shows a schematic view of the manufacturing system which is modelled in the following. This part of the system consists of conveyors (drawn as rectangles), turntables (drawn as circles) and machines (drawn as squares). The complete manufacturing system in addition comprises of robots, automated handling systems and automated guided vehicles which are outside the scope of this example, for the sake of simplicity. However, they could be modelled within the same CAEX model in a similar way.
The detailed description of Unit 003 is shown in Fig. 3. The unit consists of four conveyor belts (003FB_001-4), two turntables (003DT_001-2) and one machine (003WZ_001). The conveyor belt 003FB_002 is equipped with a sensor B3_S09 (to detect the presence of a work piece) and a motor M18 to move the conveyor. Sensor B3_S09 has an interface Output, which is derived from the class Digital Output. This interface enables the sensor to send information. In this case the sensor is used for identifying a product on the belt. Motor M18 has two interfaces, bForward and bBackward, which represent binary commands from the controller. They are derived from class digital Input. In addition, the conveyor belt 003FB_002 itself has two further interfaces, Material In_Out 1 and Material In_Out 2, which are used to describe the material flow to and from the conveyor belt; they connect this conveyor belt to neighbouring conveyor belts or turntables. The level of detail of the description of Motor M18 is deliberately limited to the representation of the function of the component with regard to the conveyor belt. The internal structure of the motor is not part of the model. Therefore, the quality of the system diagnosis depends on the amount of data and information stored in the structural knowledge. The following sub-sequent section shows how structural knowledge supports the diagnosis but also illustrates the limits of this technique.

2.3. Diagnosis based on structural knowledge

The condition of a system, technical process or plant is controlled by monitoring important process variables like temperature, pressure, or speed. These process variables are measured with sensors. The deviations of the measured values of the process variables from their expected values are recognized e.g. by a condition monitoring system. In most cases one deviation causes subsequent deviations of the values of other variables, because process disturbances caused by the deviation of one variable are transported by product and/or energy flows and physical connections of units through the system and affect other parts of the system and their values. As a result, faults and disturbances occur at different points of the systems and not always where they were generated. The task of diagnosis systems after detecting disturbances is to find the cause of the disturbance or at least to limit the area of origin.

A CAEX-based diagnosis offers the possibility of using computational diagnosis algorithms for tracking the way of deviation propagations, based on the structural knowledge about the system. Internal links which describe the structure of the system offer the possibility of tracking faults backwards along these links in order to find causal relationships in plant-wide disturbances [12].

2.4. Limitations of the structural knowledge

Diagnosis based on structural knowledge delivers an extensive fault diagnosis by backward reasoning along the possible paths of faults and deviations. The determination of the root cause is possible, if it can be assigned to a component or unit. As explained in [3], process-faults due to incorrect operation are hard to detect and identify. The following example shows the disadvantage of structural-based diagnosis without process knowledge based on the example from Fig. 1. A possible problem in the plant could be that the amount of goods of the interim storage at Output E1 is low over a long period. The possible causes for this effect could be (i) that the conveyor belt is out of order due to damage, (ii) there are no products being supplied from the warehouse and (iii) the interim storage at E1 should not be filled with products for some reason. A possible damaged drive unit, which is responsible for (i), can easily be detected by monitoring the unit and its components. The second possible cause (no products being supplied from the warehouse) can be determined by a continuous monitoring of the stock of the warehouse. Finally (iii) could be caused due to process-specific design. The problem is that neither the structural knowledge nor the monitoring/diagnosis-systems contain any information concerning the technical process to verify the third cause.
The motivation to integrate process knowledge in the diagnosis should be explained by another example, which deals with a mixing process in a process plant (Fig. 4). After the second mixing process in Mixing Unit (2), the product feature viscosity might deviate from its set point. The set of plant-specific causes for this deviation comprises e.g. corrosive heat elements or broken stirring blades, so that they cause an incorrect heating or mixing process. These possible causes can be derived from the structural knowledge. Both root causes can be detected e.g. by deviations of the power consumption of the heat elements or the mixer motor, respectively. The causal relationship between the viscosity deviation and wrong temperature, wrong mixing speed or even an incorrect process sequence of dispensing the product (1-5) into the vessels cannot be reasoned without process knowledge.

Both examples, manufacturing and chemical process, show that the number of possibly detectable and traceable root causes is limited if the diagnosis is based only on structural knowledge. The number of possible root causes which can be related to a particular deviation can be increased by the integration of process knowledge. For the usage of already existing process knowledge, the VDI/VDE-guideline 3682 “formalized process description” is suitable and is explained in the next section.

3. Definition and Description of Process Knowledge

This section explains the term “process” and introduces a method for the graphical and object-oriented description of a process.

3.1. Definition of a Process

In this contribution, the term “process” is used according to IEC 60050-351, which defines a process as following [13]:

“Complete set of interacting operations in a system by which matter, energy or information is transformed, transported or stored.”

For the detailed description of a process it is necessary to have a suitable system boundary to separate it from the environment. This enables the user to identify the input and output variables of the system and, thus, of the process which is carried out in the system. The system boundary offers the advantage to decompose a system into different sub-systems. This enables a detailed description of the system and identification of interactions between the objects inside and with the environment.

3.2. VDI/VDE-Guideline 3682 “formalized process description”

The engineering process of automation systems is based on the division of labour between different subsections (e.g. mechanical, electrical). The engineering results of these sections building the working basis for the following sections. Hence, a general and formalized description is required which is domain independent and easily understandable to all engineers involved and usable throughout the life-cycle of the system. Accordingly the description contains information for the engineering process as well as the operation [14]. The VDI/VDE-guideline 3682 offers a description method for describing processes with a defined amount of symbols and rules to combine the symbols. Besides the graphical description, the guideline defines an object-oriented information model for data storage and administration. Fig. 5 shows the classes of objects defined by the guideline: operators (=process-operator, technical resource), states (=product, energy) and relations (=flow, utilization, system boundary). The utilization (U) describes a bidirectional correlation between the process operator and its technical resource.

![Figure 4. Schematic plant for a mixing process.](image)

![Figure 5. Graphical symbols defined in the guideline [14].](image)
The description of the technical process starts with the graphical modelling of the process. The system boundary defines the interactions with the systems environment. Inside the system boundary the process is described by a defined quantity of operators \( O \), Resources \( T \), and states \( Z \) (Product \( P \) and Energy \( E \)). Both, operators and states are interconnected by directed arcs \( F \). Besides a graphical representation, the process can be described by a mathematical model:

\[
O = \{O_1, O_2, \ldots, O_n\} \\
Z = \{P_1, P_2, \ldots, P_m, E_1, \ldots, E_k\} \\
T = \{T_1, T_2, \ldots, T_s\} \\
F \subseteq (O \times Z) \cup (Z \times O) \\
U \subseteq (O \times T)
\]

This graphical description is comparable to a signed directed graph (SDG), i.e. Petri Nets. States define the input and output variables of the system and are only connected with a process operator. The transformation of products and energy is represented by the process operator, which uses a technical resource to carry out the operation. The object-oriented information model is shown in Figure 6 as a class diagram, it represents the hierarchies as well as the relationship between the system components simultaneously. For the extensive description and continuous application of the technical process over the engineering process it is necessary to further detail the graphical symbols by attributes. The guideline defines two different attributes: identification and characteristics. The difference of the attributes is their quantity of use. Each operator and state contains only one identification-attribute with e.g. unique ident, long-/short-name and reference. The expression reference refers to states, operators and system boundary and contains therefore implicit the causal context of the process.

The second type of attributes, the characteristics, consists of the category, the descriptive part and the relational part. The characteristic compared with the identification is used to describe the character of the operator or state and is not limited to the quantity of 1. Each single attribute allows a more detailed description of the objects of the technical process. The focus of the paper is on the descriptive part which describes e.g. set points of values like temperature, colour, weight, residence time in combination with the declaration of its threshold or critical values.

With the introduction of the information in [15], it is possible to describe process steps which are performed simultaneously or alternatively. Information can be used for the description of the coherence between single process steps. The proposal for a graphical representation of the information is a blue-coloured hexagon. The class information is not part of the guideline but it is a reasonable extension of the guideline.

3.3. Describing processes with formalized process description

Although the process description has its origin in process engineering, Ulrich et al. [16] investigated the description of discrete manufacturing process successfully. Hence, the process model of a manufacturing process can be integrated into manufacturing system diagnosis. Referring again to the manufacturing diagnosis of the previous section, possible root causes are detected during the diagnosis. The causes (i) that the conveyor belt is out of order due to damage and (ii) that there are no products being supplied from the warehouse can be detected with the use of structural knowledge. The cause (iii) that the interim storage should not be filled with products concerns the production process and cannot be identified just with structural knowledge.

A sample from the production process is shown in Fig. 7. For the sake of simplicity, only the top level
process without the decomposed processes is shown. As it can be seen, the process defines two different ways of discharging product B4 from Unit 005. In this case, the information represents important information concerning the process. The content of the information is explained in Chapter 4.

Fig. 8 describes the process of the mixing process. In this case the problem arises after the process Mixing 3. For the production of product G there are several single pre-products necessary. At the beginning two products (A, B) are mixed (Mixing 1) and heated (Heating 1) and forming product C. After completing the process steps product D is added to C1 and mixed together to product E. The product E is then a pre-product and mixed with product F to the end-product G. As written in Chapter 3 the product G might deviate from its desired viscosity set points.

3.4. Motivation

As described in the previous section, system diagnosis is based on different methods and uses different quantitative and qualitative mathematical models [17] or models with recorded data [18]. The number of these models and the implicitly contained knowledge is often insufficient to identify the root cause of the fault. Especially faults which are generated due to false operation, i.e. wrong process applications, are hard to determine [3]. The process description comprises besides the target process, as a graphical figure, also process-specific data in terms of an information model. This extensive process model with the causal context between process operations by state flows on the one hand, and on the other hand the causal context of the operation and its assigned technical resource, which represent the hierarchical structure indirectly, is appropriate for diagnosis actions.

4. Use of the Process Knowledge in Systems-Diagnosis

With the integration of process knowledge an enlargement of sets of the root causes is possible. This section shows how process knowledge of both examples of section 2 can be applied for an advanced diagnosis.

4.1. Manufacturing Process

The problem of the process of the manufacturing plant (Fig. 1) affects the discharging process of the products to an interim storage. The problem of the diagnosis in Section 2 was that the structural knowledge contains no plausible indication why the products are not discharged to the interim storage at Output E1. With the integration of process knowledge concerning the whole process, a process step or the order of manufacturing can be used to explain possible causes. With the information symbol (blue) I-1 shown in Fig. 7 it is described that Output E1 is only used if the interim storage at Output E2 is completely filled. The second information I-2 is used for the case if the manufacturing result of 1, 2 or 3 was not successful. This constraint could be a possible process-specific cause for the empty interim storage at Output E1. This result must be evaluated at the end of the diagnosis. With the availability of the entire production process a fault caused by a single operator can be traced back along the process chain by using process knowledge and structural knowledge containing the component connections. This enables to isolate a root cause especially in a distributed assembly line.

4.2. Chemical Process

The set of root causes for identifying the process result of bad viscosity can be classified into component-based and process-based causes. Whereas component-based causes can be identified by using structural knowledge, process-based causes require the examination of process knowledge.

4.2.1. Diagnosis of process sequence

Figure 8 shows the graphical sequence of operations. Here it becomes clear that the order of dispensing the single products and the execution of the
operations Mixing 1 and Heating 1 is important. The
diagnosis with process knowledge could provide the
result that the constraints for each single process is not
adhered to or that the order of process Mixing 2
combined with Dispense 3 of product D was
interchanged with process Heating 1. This might result
in a different viscosity of product E and could have a
significant influence to the subsequent process
Mixing 3 with product F which leads to an undesired
production result of G. With the integration of process
knowledge, the order of the production process can be
checked. Thus, the possible cause of wrong added
products or interchanged process steps can be
investigated i.e. compared with recorded process data.
This cause cannot be detected with structural
knowledge alone.

4.2.2. Diagnosis of process values
Another advantage of the integration of process
knowledge is the availability of the process attributes
shown in Table1. These data and information are
useful to compare the recorded process data with its
target values. For example, the viscosity of the end-
product depends on each pre-product (1-5). Each
product is described by different attributes like target
quantity or grain diameter and have significant
influence on the process quality. If the diameter of the
pre-product 5 is too high, a deviated viscosity of the
end-product is possible. Nevertheless the described
assumption and derivation of cause-effect-interrelation
must be reviewed. Thus process knowledge offers the
possibility to widen the set of possible causes in the
diagnosis.

5. Conclusion
With this contribution it is shown that the
integration of process knowledge and combination with
structural knowledge can improve system diagnosis.
With the description of processes according to
VDI/VDE-guideline 3682, a graphical and object-
oriented representation of process knowledge is
available. This knowledge representation allows to
model process knowledge in a way that it can be
evaluated to provide useful information for diagnosis
applications. Both examples, from manufacturing and
process industry applications, show that the content of
process-specific information yields an enlargement of
the amount of possible root causes, which comprises
component/plant-specific and process-specific causes.

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Table 1. Sample of the process-specific
attributes of the mixing process

<table>
<thead>
<tr>
<th>Process: Mixing 1</th>
<th>Attributes</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mixing Time 1</td>
<td>60</td>
<td>s</td>
</tr>
<tr>
<td></td>
<td>Mixing Time 2</td>
<td>40</td>
<td>s</td>
</tr>
<tr>
<td></td>
<td>Speed Mixing 1</td>
<td>100</td>
<td>s^2</td>
</tr>
<tr>
<td></td>
<td>Speed Mixing 2</td>
<td>300</td>
<td>s^2</td>
</tr>
<tr>
<td></td>
<td>Max. Temperatur</td>
<td>50</td>
<td>°C</td>
</tr>
<tr>
<td>Process: Heating 1</td>
<td>Heating Time 1</td>
<td>45</td>
<td>s</td>
</tr>
<tr>
<td></td>
<td>Target Temperatur</td>
<td>45</td>
<td>°C</td>
</tr>
<tr>
<td>Process: Mixing 2</td>
<td>Mixing Time 1</td>
<td>25</td>
<td>s</td>
</tr>
<tr>
<td></td>
<td>Mixing Time 2</td>
<td>45</td>
<td>s</td>
</tr>
<tr>
<td></td>
<td>Speed Mixing 1</td>
<td>120</td>
<td>s^2</td>
</tr>
<tr>
<td></td>
<td>Speed Mixing 2</td>
<td>240</td>
<td>s^2</td>
</tr>
<tr>
<td></td>
<td>Max. Temperatur</td>
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<td>°C</td>
</tr>
<tr>
<td>Process: Dispensing 5</td>
<td>Target quantity</td>
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<td>kg/min</td>
</tr>
<tr>
<td></td>
<td>grain diameter</td>
<td>2.5</td>
<td>mm</td>
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