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Diagnosis based on Fault Event Models

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Abstract

Most of model-based diagnosis systems use intended behavior models of the target systems. The reasoning results of such systems are restricted to only misbehaviors as consequences of the faults, and thus the deeper causes underlying the misbehaviors remain untouched. We define faults as the abnormal phenomena representing transitions from the intended behavior to misbehaviors, called *fault event*. In this article, a diagnosis based on the fault event models is proposed. The fault event models represent generic fault events which could commonly occur in components. The method provides causal chains of fault events which explain why and how the component has reached the state misbehaving. Moreover, we show an example of the reasoning integrated with the conventional methods. The integrated reasoning system can uncover the deeper causes underlying the faults detected by the conventional methods.

Introduction

The performance of a model-based diagnosis system depends on content of the system descriptions. Most of them are based on intended (correct) behavior models and define a fault as "anything other than the intended behavior"(Davis 1984; de Kleer & Williams 1987; Hamscher et al. 1992; Reiter 1987). Such systems, however, do not try to explain why and how the fault has occurred. For example, the fault of a shaft of a turbine could be detected as abnormal behavior of the intended model. On the other hand, the causal chains which have caused the abnormal behavior, for example, an invasion of some fragments of substance (e.g., dust) has caused a stuck of the shaft, could not be derived from the intended model. Such causal chains consist of unintended phenomena (e.g., invasion and stuck) which could occur with faults. The diagnosis systems using only the intended behavior models cannot cope with such phenomena. The reasoning results of such systems are restricted to only a set of components with misbehaviors which are consequences of the faults, and thus the deeper causes underlying the detected misbehaviors remain untouched. Figure 1 illustrates the limitation of diagnosis based on the intended behavior models.

The fault models are indispensable to reasoning of the abnormal phenomena and uncovering the underlying causes. The conventional fault models, however, are inadequate from the viewpoint of reusability and competence. The conventional fault models are categorized into two types. One is represented by physical parametric fault models of model-based systems such as GDE+(Struss & Dressler 1989). The fault models represent behavioral consequences of the possible faults of each component (fault modes). Our method is beyond the approaches employing such fault modes which cannot explain why the behavior come to a fault mode. The other type of the fault models is represented by empirical diagnostic rules representing direct symptom-fault associations. Some of rules represent abnormal phenomena, which enable the reasoner to derive deeper causes. Such rules, however, tend to depend on the target system and thus they are not reusable. In summary, the fault models should be reusable and represent not only the consequences of the faults but also the abnormal phenomena which have caused the faults.

The lack of abnormal phenomena model is because of the inadequate definition of the fault. The fault means not only misbehaviors as consequences of the faults but also the transitions from the intended behavior to the misbehavior. We call such transitions *fault events*. The fault of the target system can be viewed as the causal chains of the fault events among components. The *fault event models* are generalized fault events. For example, the fault event "adhesion" can be generally defined as the phenomena in which the existence of some small fragments in the neighborhood of a component causes the change of the shape of the component.

The fault event models have the following three advantages. First, knowledge of abnormal transitions represented by them enables the reasoner to derive the deeper causes of the fault. Furthermore, it uncovers unintended relations (interactions) underlying the in-

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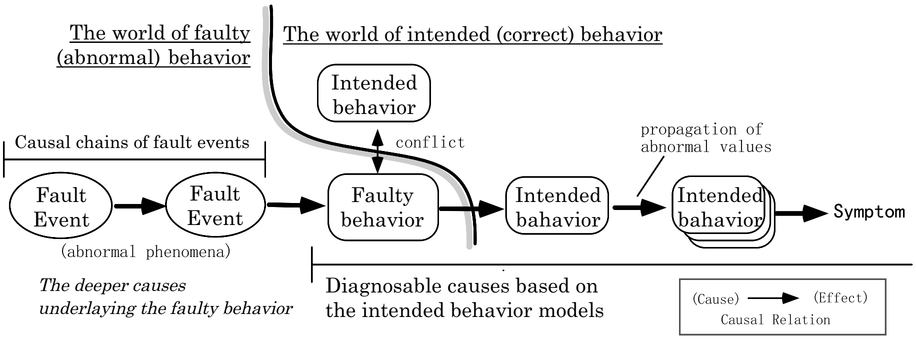

Figure 1: The limitation of the intended behavior models

tended behavior model. For example, the fault event "leak" makes unintended interactions among components which are not described in the intended behavior model. According to such unintended interactions, the faulty component which is the deeper cause of a faulty component which the conventional method could detect can be detected. A concrete example of such interactions is shown later. Next, because they represent primitive causal relations from the viewpoint of the fault event and they are described by generalized parameters, they are generic and reusable. Lastly, they are represented in terms of conceptual attributes such as shape and existence which enable the reasoner to cope with complex phenomena, such as breakage, which is difficult for conventional model-based approaches based on physical parameters.

In this article, a diagnosis method based on the fault event models is proposed. Given observed symptoms, the method provides causal chains of fault events which enable explanations why and how the component has reached the faulty state. For example, consider a fault in which a turbine blade is broken. The following statement shows one of the possible causal chains for the broken turbine blade. Quoted terms represent the fault events.

> The turbine shaft has been subject to "abrasion" in the long term, which results in the "aberration" of the position of the blade. Then, the "hit" of the blade against the turbine casing causes "breakage" of the blade.

The reasoning based on the fault event model is complementary to the conventional methods whose basis is an intended behavior model. This article shows a framework of the reasoning system which consists of the conventional method and the reasoning based on the fault event models. The integrated reasoning system can uncover the deeper causes underlying the faults detected by the conventional methods.

Fault Events

A Fault Event

A fault event of a component is defined as a state transition from the normal state to a *faulty state* of the component. A component is in the faulty state, when it satisfies both of the following conditions.

1. At least one of the outputs of the component takes abnormal value.
2. The behavior of the component is abnormal.

A fault event consists of a *causative state*, a *process* and a *resultant state*. The causative state represents the influence which causes the state transition. The process represents the state transition between the causative state and the resultant state. The resultant state represents the faulty state caused by the state transition. For example, the causative state of the fault event "aberration" is the state in which the pressure exerted on the component is greater than the intended one. It causes the process, that is, the component moves from the intended position to the abnormal one. Then, a resultant state appears in which the position of the component is abnormal.

The state transitions of the fault events are irreversible. In other words, the faulty state does not return to the intended state even if the influences which caused the fault event disappear. In cases of reversible transitions such as some kinds of thermal expansion, the abnormal states are called "semi-faulty states".

Causal Chains of Fault Events

A target system can be viewed as a set of components. The fault of the system can be represented by the causal chains of fault events which occur on each component. Figure 2 shows an example of a causal chain of fault events. The system consists of the three components, c_1, c_2 and c_3. The abnormal influence a_1 is propagated to the component c_1 and the state of the c_1 becomes the state s_1. The s_1 causes a fault event on the c_1 in which the causative state s_1 changes into the faulty state s_2. Next, the influence of the s_2 is propagated to the c_2. In this case, no state transition

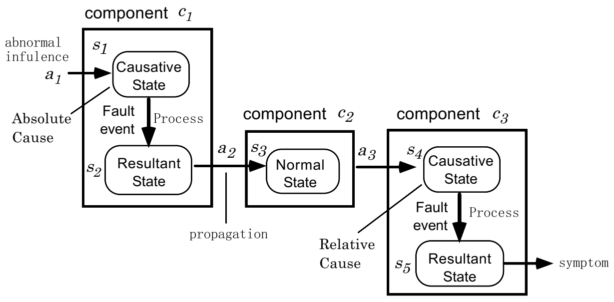

Figure 2: An example of a causal chain of fault events

occurs at c_2, and c_2 outputs the abnormal influence a_3. When a_3 is propagated to the c_3, a normal state of the c_3 changes into the faulty state s_5.

A *fault* in a system is represented by a fault event and a faulty component. In this example, the system has two faults and the faulty components are c_1 and c_3. A *cause of a fault* is defined as the causative state of a fault event. The causative state of a fault event is called the *relative cause* of the fault event and the resultant state. The *absolute cause* represents such a causative state that no fault event causes the state in the target system. In the example, the absolute cause of the faults is the state s_1.

The diagnosis task can be defined as the process which detects all plausible causes of the fault events which have caused the given symptoms. There are, however, some cases where no cause of a fault is found by the diagnostic process. For example, a target system which has no fault event but an abnormal input influence also has abnormal symptoms.

Fault Event Models

A fault event model represents a generic fault event. It consists of a term representing the fault event, a causative state, a process and a resultant state. It means that if there is a component matching the condition of the causative state, then the process probably occurs, as the consequence, the status of the component changes into the resultant state. In other words, a fault event model represents general faulty phenomena which could occur commonly in components. The term is a noun representing the fault event for humans.

The causative state represents conditions for the fault event. A state is a set of four-tuples <object, attribute, relation, value>. The object is "component" or "environment". The "component" can match all the components in the target system. The "environment" represents the neighborhood of a component. There are some conceptual attributes which do not directly correspond to physically measurable attributes. For example, the attribute "shape" of a component takes either "normal" or "abnormal" as its value. On the other hand, an environment has attributes such as "temperature", "pressure" and "fragment". The last attribute takes either "exists" or "not-exist" as its value which represents some small fragments of substance (e.g., dust) exist (or not) in the environment of a component.

The causative states are categorized into two types, namely *necessary* states and *accelerative* states. The fault event will not occur without the former states. The latter states just accelerate the event. The resultant states are categorized into two types, *direct* states and *associated* states. The latter states are not included in the meaning of the term of the fault event.

A process represents the state transition from the causative state to the resultant state. A description of a process consists of an object, a term and a time-interval. The term is a verb representing the process for humans. Most of them are identical with the verbalized terms of the noun term representing the fault events. The time-interval takes one of "long", "short" and "instant", which represents the necessary time interval for the event.

We have described 31 fault event models. Table 1 shows a sub-set of them. "object:attribute" denotes the attribute of the object. The "comp" and "env" are the abbreviation for the component and the environment, respectively. The mark [A] denotes "accelerative" or "associative". See "adhesion" in Table 1 and Figure 3, for example. When some fragments exist in the neighborhood of a component, the fragments probably adhere to the component in the short term. As associative consequences of the process, the shape of the component will be changed to abnormal and the resistance for friction becomes greater than that of normal.

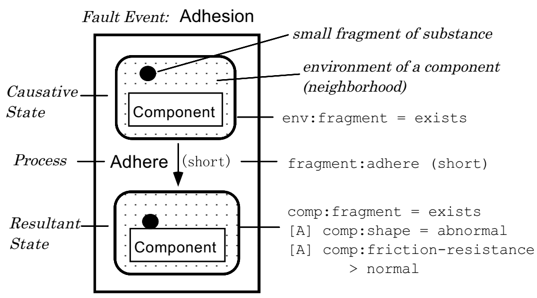

Figure 3: A fault event model: adhesion

Reasoning based on the Fault Event Models

The fault event models make the reasoning on the causal chains of the fault events. There are two reasoning processes, the retrospective reasoning and the prospective reasoning. The former generates plausible causes which have probably caused the given state.

Table 1: Examples of the fault event models

Vocabulary	Causative States	Process	Resultant States
aberration	env:pressure > normal comp:shape ≠ normal	comp:move (short)	comp:position ≠ normal
abrasion	[A] comp:position ≠ normal	comp:abrade (long)	comp:shape ≠ normal, [A] env:temperature > normal, [A] env:fragment = exists
adhesion	env:fragment = exists	fragment:adhere (short)	comp:fragment = exists [A] comp:shape ≠ normal, [A] comp:friction-resistance > normal
breakage	comp:strength < normal or env:pressure > normal	comp:break (short)	comp:shape ≠ normal [A] env:fragment = exists
collision	env:fragment = exists	fragment:collide (instant)	env:pressure > normal
corrosion	[A] env:chemically-activated-fragment = exists	chemically-activated-fragment corrode (long)	comp:strength < normal, [A] comp:shape ≠ normal
hit	comp:position ≠ normal	comp:hit (instant)	env:pressure > normal
invasion	comp:shape ≠ normal	fragment:invade (instant)	in-env:fragment = exists
leak	comp:shape ≠ normal	fragment:leak (instant)	out-env:fragment = exists
stuck	comp:friction-resistance > normal	comp:stick (long)	comp:movement ≠ normal

The latter generates all resultant states to be caused by the given state.

Each reasoning process has two steps, that is, the matching step and the evaluation step. In the retrospective reasoning, the matching step searches for the fault events which have the resultant state matching the current state. The fault events searched for are events which have probably caused the current state and thus they are a part of plausible causal chains for the current state. The causative states of them are the relative causes of the current state. In cases where there are more than one plausible fault events for a current state, the relations among them are OR-relationship. The evaluation step generates new current states according to the description of the causative state of the fault events. Then, the further matching step is invoked for the new current states in order to detect deeper causes.

Consider the case where the position of a component is abnormal. Figure 4 shows a part of the causal chains which have caused the abnormal position. Given the faulty state with "component:position ≠ normal", the retrospective reasoning engine searches for the fault events which change the position of the component. Then, some fault events such as "aberration" and "fall" are found as plausible events which have caused the abnormal position. Because the causative state of "aberration" implies that the pressure exerted on the component is greater than the normal one, the engine next searches for the events which exert pressure on the component. Then, the fault events such as "collision" and "push" are found. As the result, it is generated as one of the plausible causal chains that some fragments have collided with the component and then the components have moved to the abnormal position.

In the case of the prospective reasoning, the reasoning is done in the reverse direction. The engine searches for the events that have a causative state which matches the given state. Next, the evaluation step generates new current states according to the description of the resultant state of the events.

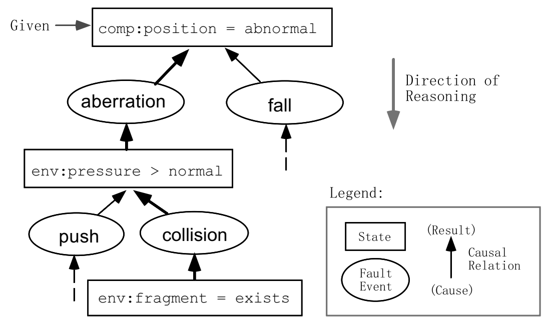

Figure 4: The causal chains which have caused the abnormal position

There are cases where no event is found in the matching step, because the attributes of the fault events are described in different grain sizes for generality. In such cases, the attributes are generalized according to the hierarchy of the attributes of the fault event. The knowledge representing such hierarchical relations between attributes is called the hierarchical attribute knowledge.

Integrated Diagnosis Method

We propose an integrated diagnosis method which has two reasoning methods. One is the method based on the fault event models discussed thus far, called the fault event level. The other is an ordinary model-based method using intended behavior models in terms of qualitative constraints (Kitamura et al. 1996a; Kitamura et al. 1996b), called the constraint level. Figure 5 shows the framework of the integrated diagnosis method. We mention the model and the reasoning method at the constraint level in the paragraph below. Next, the reasoning process and the interpretation knowledge for conversions between two levels will be discussed in that order.

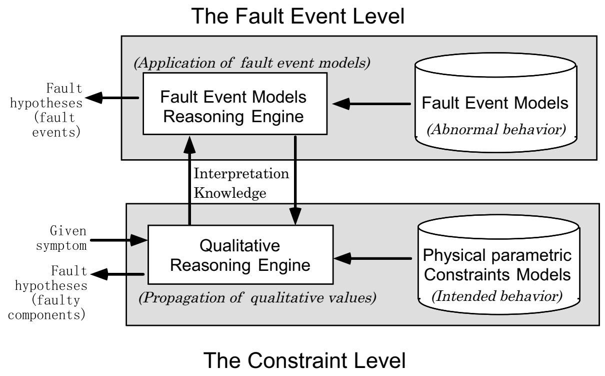

Figure 5: The framework of the integrated diagnosis method

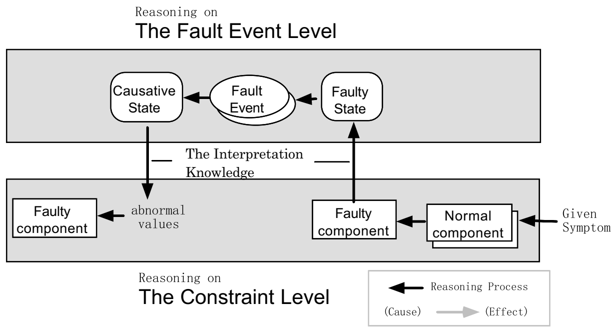

Figure 6: Causal chains derived by the integrated retrospective reasoning

The constraint level

At the constraint level, the knowledge base contains qualitative component models representing their intended behaviors. A component model consists of a set of physical parameters, qualitative constraints over parameters, ports for connections and *causal specifications* representing causal properties of the parameters. The "physical parameters" means attributes which directly correspond to physically measurable quantities. A parameter takes one of the three qualitative values related to the deviation from a normal value. [+]([-]) represents a quantity greater(less) than the normal value, i.e. abnormal values. [0] represents a quantity equal to the normal value. The normal value of a parameter is defined as a permitted range of the parameter when the overall system is in a normal equilibrium state without any perturbation. A causal specification of a parameter represents the possibility of it to take causal roles where two flags C and E are used to denote "can be a cause" and "can be an effect" of other parameters in the component respectively and "~ " is a negation symbol. A concrete example of component models will be shown in the next section.

The reasoning engine at the constraint level is based on qualitative reasoning techniques(de Kleer & Brown 1984; Kuipers 1994; Iwasaki 1986). The reasoning method is categorized as a type of the reasoning method proposed by de Kleer and Brown (de Kleer & Brown 1984). On the basis of the device modeling, it has two reasoning processes, that is, the intra-component reasoning and the inter-component reasoning. Given abnormal values propagated from other components, the intra-component reasoning process determines values of other parameters in the component. According to constraints and the causal specifications, abnormal values are propagated to other parameters in the component. In the inter-component reasoning process, on the other hand, abnormal values are propagated to parameters of neighboring components according to connections between ports. It can infer finer-grained causal ordering among physical phenomena in transition states and feedback loops on the basis of seven units of time resolution. For more detail, see (Kitamura et al. 1996a; Kitamura et al. 1996b).

The Reasoning Processes

Our diagnostic method consists of two processes, the fault-hypotheses generation and the fault-hypotheses verification. The generation process derives plausible causes of the fault covering the given symptom. The verification process generates all the possible symptoms to be caused by the fault-hypotheses and checks predicted values against actual values. In this article, we concentrate on the the fault-hypotheses generation process.

The integrated fault-hypotheses generation process consists of two level reasoning, the constraint level and the fault event level. Figure 6 shows an example of causal chains derived by the reasoning process. Given the physically parametric symptom, the qualitative reasoning engine at the constraint level retrospectively propagates abnormal values according to the intended behavior model. First, the given symptom is propagated to the other parameters in the component. Next, the abnormal values are propagated to the neighboring components. The reasoning results at the constraint level are a set of abnormal parameters whose values have no deeper cause at the level, that is, the absolute causes at the level. Then, the causes are converted to the fault event model according to the interpretation knowledge in the paragraph below. At the fault event level, causal chains of fault events are derived on the basis of the fault event models. In the case where causative states at the fault event level can be converted to the constraint level, the more deeper causes are derived at the constraint level as shown in Figure 6.

The Interpretation Knowledge

The conversions between physical parameters and faulty states are done according to the interpretation knowledge. The following relations are examples of the interpretation knowledge.

1. IF humidity = [+] THEN environment:water-vapor = exists
2. IF turbine-efficiency = [-] THEN component:shape $\neq$ normal

The first one represents the equivalent relation between the physical parameter "humidity" and the existence of water vapor. This is independent of the component. On the other hand, the second one depends on the turbine and represents a causal relation.

In the retrospective reasoning process, the conversions from the constraint level to the fault event level are done when there is no deeper cause of a state at the constraint level. On the other hand, those from the fault event level to the constraint level are done when there is an interpretation knowledge applicable to a causative state and new abnormal values at the constraint level will be generated. Because the concrete constraint models are more informative than the generic fault event models, the reasoning engine prefers the constraint models.

An Example of Reasoning

In this section, we show an example of the integrated reasoning. The target component is a steam turbine of a power plant. The turbine is connected to a generator and a super-heater. The symptom given in this example is "the output power of the generator is lower than normal value".

The Constraint Level

First, the engine focuses on the generator whose output is identical with the symptom and generates a relative cause, that is, the revolution of the shaft of the turbine is lower.

Next, the engine reasons about the turbine. Fig 7 shows the constraint model of the turbine. Given the revolution of the shaft is lower, that is, `n` = `[-]`, the reasoning engine derives that `e` = `[-]`, `flow` = `[-]` or `v` = `[-]` according to the constraint (1). Then, the following causes are generated:

- **Absolute Cause:** `e` = `[-]`
- **Relative Cause:** `flow` = `[-]`, `qin` = `[-]`, `pin` = `[-]`, `pout` = `[+]`

The relative causes such as `flow,qin` are associated with other components. Then, the abnormal values are propagated to the super-heater which is an upper component.

On the other hand, no deeper cause of the decreases of the turbine efficiency is derived at the constraint level. Then the engine converts the state to the fault event models according to the interpretation knowledge. In the paragraph below, we show an example in the case of an abnormal shape converted from the decreases of the efficiency.

Name: turbine
Port:

symbol	*connected component : port*
in	superheater : out
out	condensor : in
gen	generator : in
flow	flow : receiver
press	press : receiver

Parameters:

symbol	*description*	*causal spec.*	*port*
`n`	shaft revolution	C$\tilde{\text{E}}$	gen
`qin`	inlet heat	C$\tilde{\text{E}}$	in
`qout`	outlet heat	$\tilde{\text{C}}$E	out
`flow`	flow rate	C$\tilde{\text{E}}$	flow
`pin`	inlet pressure	C$\tilde{\text{E}}$	press
`pout`	outlet pressure	C$\tilde{\text{E}}$	press
`e`	efficiency	C$\tilde{\text{E}}$	
`v`	velocity	CE	

Constraints:

```
n = e * flow * v                (1)
v = (pi - po) * (qin - qout)    (2)
```

Figure 7: The constraint model of the turbine

The Fault Event Level

Figure 8 shows a part of a retrospective reasoning at the fault event level which starts with the abnormal shape. First, the engine generates the fault events which have resultant states matching "component:shape $\neq$ normal". For example, "adhesion" is derived as one of the possible fault events. It means that the existence of some fragments has caused "adhesion" and then the shape becomes abnormal. Next, the engine views the causative states of the generated events as the resultant states and searches for the fault events to cause them. In this example, the existence of some fragments which is the causative state of the adhesion may be caused by the fault events such as "invasion" and "abrasion". In the case where the turbine is new, the "abrasion" could not be plausible according to its description of the necessary time interval.

In the case of "breakage", the reasoner searches for the fault events which have the resultant state which matches "component:strength < normal" or "environment:pressure > normal". Then "corrosion", "collision" and so on are derived. Next, the engine searches for the event matching "environment:chemically-activated-fragment = exists" which is the causative state of the "corrosion". As there is no further event, the attribute is generalized to "fragment". Then, "invasion" of chemically-activated-fragments are generated.

The causative state of "collision" is an existence of fragments. According to the interpretation knowledge that "IF humidity > normal THEN environment:water-vapor = exists", the engine con-

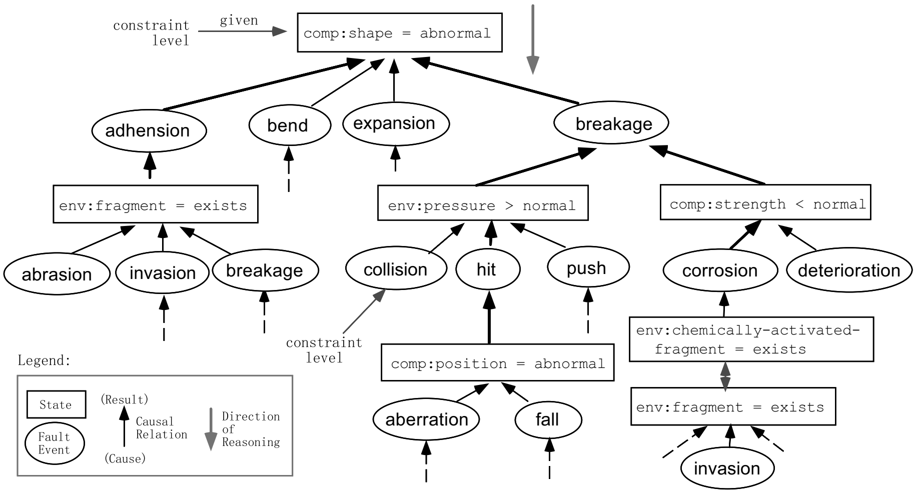

Figure 8: The causal chains which have caused the abnormal shape

verts the state to the physical parameter. At the constraint level, the fault that outlet temperature of the super-heater is lower than that of normal is detected.

The Reasoning Results

Given the abnormal output power of the generator, 3 fault hypotheses at the constraint level and 28 fault hypotheses for the turbine at the fault event level are generated. Then, they are verified by the verification process. The reasoning results for the turbine cover all the faults of a turbine listed in a technical book on power plants. The following statement represents a causal chain generated by the reasoning engine.

> First, the super-heater fails, then outlet temperature of the steam becomes lower than the normal value. In turbine, the lower temperature causes over existence of water-vapor and then "collision" of water-vapor with turbine blade, which results in the "breakage" of the blade. Then, the efficiency of the turbine decreases and then the revolution of the shaft becomes lower than the normal value. Eventually, output power of the generator decreases.

In this case, the deeper causes of the decrease of the efficiency of the turbine such as "collision" and "breakage" are derived. Although the fault hypothesis "super-heater fails" itself is physical parametric one, the causal chain between it and the decrease of the efficiency is hidden at the constraint level.

Related work and Discussion

Most of conventional model-based systems such as GDE(de Kleer & Williams 1987) use intended behavior models represented by physical parametric constraints. Our method based on the fault event models has the following advantages over such conventional systems:

1. Explanation why the fault has occurred by causal chains of fault events is possible.
2. Interaction between the environment and the component is dealt with.
3. Complex phenomena represented in terms of conceptual attributes can be dealt with.

First, the system can explain causal chains which have made the components abnormal, that is, the deeper causes of the faults. Furthermore, as shown in the example mentioned in the previous section, according to unintened causal chains, the faulty component (the super-heater) which is the deeper cause of the faulty component which the conventional method could detect (the turbine) is detected. Secondly, our method can reason about the interactions between the component and its environment such as adhesion. Because most of conventional systems use the device models only, they cannot reason about such phenomena. Lastly, the fault event models are represented in terms of conceptual attributes such as shape and existence and thus our method can easily cope with complex phenomena such as breakage. While the constraint-based system can cope with such phenomena, it is difficult to represent such phenomena by physical parametric constraints and reason about them.

The fault event models are, however, generic and coarser than the constraint models. The competence of this method with respect to resolution is not high. Our method enumerates fault events which have possibly caused the symptom. Therefore, this method is complementary to the conventional method.

The fault event model is viewed as a kind of fault models. Our method based on the fault event models has the following advantages over the two types of conventional fault models, that is, physical parametric fault modes of model-based systems such as

GDE+(Struss & Dressler 1989) and empirical diagnostic rules representing direct symptom-fault associations.

1. Reusability of models.
2. The deeper causes of the fault models can be derived.
3. Abnormal inter-component phenomena can be dealt with.

First, the conventional fault models depend on components and/or target systems and thus one should describe the fault models for each component or system. The fault event models represent primitive causal relations from the viewpoint of the fault event and they are described by generalized parameters. Thus, the fault event models are generic and reusable. Composing the primitive fault events, the reasoning engine can generate symptom-fault associations which traditionally represented by the empirical diagnostic rules. Secondly, the fault modes of model-based systems represent behavioral consequences of the possible faults of each component. Thus, the deeper causes underlying the detected fault modes remain untouched. Our reasoning engine, on the other hand, generates causal chains of abnormal phenomena according to the fault event models representing abnormal transitions to the faulty states and thus derives the deeper causes of the fault. Lastly, because most of model-based systems trace only inter-component connections which are explicitly described in the model, abnormal (unintended) inter-component interactions such as those caused by structure faults cannot be dealt with. The fault event models include abnormal interactions among objects such as hit and invasion. It enables the reasoner to cope with abnormal interactions caused by structure faults.

In (Böttcher 1995), abnormal inter-component interactions called *hidden interactions* are discussed. His hidden interaction models for the fluid domain such as leak can be viewed as a kind of generic fault events between components. Our fault event models include such cases as shown in Table 1.

The QP theory(Forbus 1984) introduces the concept of "process". The fault event can be viewed as a special kind of the process. The fault events can represent discrete phenomena such as breakage. Moreover, our method deals with accelerative states and associative states for diagnosis.

The framework reported in (Purna & Yamaguchi 1996) uses knowledge called *naive physics* representing general causal relations between naive concepts and phenomena causing them. For example, "exist" of liquid is caused by flow of liquid, melting of solid or condensation of gas.

Summary

A diagnosis based on the fault event models has been proposed. We claim that the fault is defined as the fault event representing the state transitions to the faulty states. The 31 fault event models which are generic and reusable have been described. The integrated diagnosis method can derive deeper causal chains than the conventional one.

Currently, the set of the fault event models are built on the plant domain including pumps and turbines. Extension of our work for other domains such as electronics and mechanics remains as future work. Furthermore, in order to develop a framework to diagnose unexpected faults, an investigation on control knowledge representing probabilities of fault events is also in progress.

Acknowledgments

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