An Application of Qualitative Reasoning to Process Diagnosis:
Automatic rule generation by qualitative simulation

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ABSTRACT
AQUA, a knowledge acquisition tool for process diagnosis domain, is presented. AQUA uses a qualitative model in guiding the construction of diagnostic rule-base. Since on-line real time diagnosis of the real process plant requires a huge rule-base, systematic way of building the rule-base is proposed by a qualitative version of fault simulation on the qualitative model. The qualitative model is modified interactively by the facilities of qualitative simulation and qualitative diagnosis. In order to further enhance the knowledge acquisition process, the knowledge from which the model is constructed is divided into two types: plant-common knowledge and plant-specific knowledge.

INTRODUCTION
Recently, many tools for constructing knowledge-based systems have been developed without much consideration of knowledge acquisition. However, construction and maintenance of knowledge base becomes a major problem in building knowledge-based system. Process diagnosis, for example, requires a huge knowledge base. Building such a huge knowledge base for each different process plant is economically impractical.

Some approaches such as interactive transfer of knowledge [1,2] have been studied to facilitate knowledge acquisition process by automating low level inferences which have been done by the programmers. We also follow this interactive transfer of knowledge in modifying and refining the knowledge. Further, we use a technique of knowledge transformation from higher level knowledge (model) to lower level knowledge (rules) to lessen the task of building knowledge base. Building higher level knowledge of model is much easier than lower level knowledge of rules, since one relation in the model produces several associations of causes and effects.

We developed a knowledge acquisition tool AQUA using these techniques. AQUA consists of two subsystems: ACQ (ACQuire the model) and QUA (QUAlitative analyzer). The knowledge acquisition process is divided into two phases: model building phase and rule generation phase. The knowledge is explicitly divided into two parts: plant-common knowledge (component model library) and plant-specific knowledge (structural assignment of components). ACQ is used in the model building phase, and QUA in the rule generation phase. QUA generates diagnostic rules by carrying out qualitative reasoning [3,4] on the model such as qualitative version of fault simulation. QUA can also do the global analysis on the model such as qualitative stability analysis [5]. QUA is also used to modify the qualitative model interactively. ACQ composes the qualitative model of the target process plant by composing template models in the component model library, following the structural assignment of components.

METHODS FOR PROCESS DIAGNOSIS
Most diagnostic systems fall under one of two categories: syndrome-based diagnosis [6] or model-based diagnosis [7]. We will explain these two complementary methods by an illustrative example of a buffer tank with level control [8]. Figure 1 [6] shows a simple diagram of the buffer tank. Table 1 [6] shows the knowledge for syndrome-based diagnosis represented in the form of a decision table. The relevant faults are listed in Table 2 [6]. Each column in the table represents a syndrome-indexed rule. A syndrome consists of a combination of symptoms, and each symptom is represented by an attribute which may typically have one of three values -- e.g., high, normal, or low. These qualitative values are determined by ascertaining whether some sensory datum exceeds or falls within predetermined thresholds.

A mathematical model (quantitative model of continuous systems) which may be used for model-based diagnosis of the buffer tank is shown in Table 3. First, parameter-estimation is carried out from the monitored output of the process instrumentation. Then these estimated parameters are compared with those of preknown model. The discrepancy patterns of these estimated parameters and model parameters are used to identify the fault.

Figure 1 [6]: A Diagram of a Buffer Tank Example

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\[
\frac{dL}{dt} = a \cdot AF
\]
\[
F2 = \frac{8}{I \cdot V1 \cdot (L1)^{1/2}}
\]
\[
v1 = \gamma \cdot (L1 - \mu)
\]

\(a, \beta, v, \mu\): Appropriately chosen constants.

### Table 3: A Quantitative Model of the Buffer Tank Example

<table>
<thead>
<tr>
<th>Events</th>
<th>(1) Normal operation</th>
<th>(2) Pipe leakage between F2 and V1</th>
<th>(3) V1 by-pass open in error</th>
<th>(4) Blockage in exit line</th>
<th>(5) Leak to tank</th>
<th>(6a) Abnormal throughput high</th>
<th>(6b) Abnormal throughput low</th>
</tr>
</thead>
</table>

Table 2 [6]: List of Faults of the Buffer Tank Example

Because of the difficulty of obtaining the quantitative model and computational problems, the model-based method cannot always be used for on-line real time diagnosis of large scale plant. On the other hand, the syndrome-based diagnosis is often used because of its simplicity. In this method, however, the fault dictionary tends to become huge in real process plants and generating such tables is time-consuming task. We use a qualitative model of a particular plant to semi-automatically generate the initial set of diagnostic rules for syndrome-based diagnosis. This qualitative model is also used for qualitative diagnosis. This qualitative diagnosis is discussed elsewhere [8].

**QUALITATIVE THEORY**

The reasons for adopting the qualitative reasoning in our research are:

1. It is often difficult to obtain the quantitative model for the real process.
2. Even though the quantitative model for the system is obtained, it requires too much computation for using the model to meet the real time diagnosis.

Further, it turned out through the interview with process diagnosis experts that they use qualitative reasoning extensively in their diagnostic reasoning.

Before the development of qualitative reasoning in AI, qualitative version of system theory has been studied extensively. The signed directed graph is used for expressing a dynamical system. Many qualitative version of system theoretic concepts such as qualitative stability and qualitative observability are proposed, and their characteristics conditions are studied in terms of topological structure of the graph.

In the qualitative physics [3] of AI, they start from "physical structure". Their ultimate goal seems to find out heuristics to translate the "physical structure" to composite model (whether it is process oriented or component oriented) on which several reasoning and operations are possible. They regard the physical structure as a constraint and a process subject to the constraint. Kuipers' theory [4], however, starts from abstracting the mathematical model preserving qualitative information in the model.

Their way of translating the physical structure seems different with each other. In this stage, it is not clear to us which one is the most reasonable. Thus, we will only use the part of "qualitative mathematics" of the qualitative reasoning in AI combined with other results of qualitative version of system theory [5].

**A QUALITATIVE MODEL FOR PROCESS**

Kuipers' model abstracts over differential and/or algebraic equations. AQA's model is obtained by observing the physical system in terms of effect qualitatively, i.e. the direction of the change of effect, phase lag of the effect, and the condition when the effect is activated or disabled. This condition which identifies the changes in the structure of the model is necessary. In the case of the coolant system of nuclear power plant, for example, it is important to recognize changes in the structure of the model after the temperature of the coolant crosses over the boiling point.

AQA's qualitative model has potentially the same power for qualitative simulation as that of Kuipers'. Our model does not have explicit operational primitives such as derivatives, summation, substraction, and monotonically increasing (or decreasing) functions which are used in Kuipers' model. By restricting our representation to qualitative descriptions of physical processes, the task of mapping from some specific process plants to the model is made more direct. This may make it easier for experts, in conjunction with knowledge engineers, to build and refine a model of a process plant.

The Qualitative Model

AQA's qualitative model consists of two types of primitives, i.e. the variables (sensor value directly monitored, or other state variable needed for the model) and dynamical relation among these...
variables. Defined in more detail, 

Variable: Variable has its state, first order derivative of the state (velocity), and second order derivative of the state (acceleration) and so on. Each variable may have as many higher order derivatives as needed. Each of the derivative has qualitative values such as H (high), N (normal), L (low), or L (low) or L (low). 0 (fault not occurred). Most variables can be viewed as attribute of flow, e.g. temperature, pressure, velocity of the flow.

Interaction: Interaction is defined as the effect from one variable to the other variable. Each interaction is associated with an integer (0,1,2,...) indicating the order of the phase lag of the interaction, the sign (+,-) indicating the direction of change, and condition indicating the case when the interaction is activated or disabled. Condition is expressed as a logical combination of variables specifying the derivative and value of it.

This model can be conveniently expressed by a signed directed graph where node and arc corresponding to variable and interaction, respectively. For example, F2 -(-,0)-> AF means that if the state of F2 becomes high (low) then AF must become low (high) without no delay of time. On the other hand, AF -(+,1)-> L1 means that if AF becomes high (low) then it makes L1 increase (decrease), and thereby L1 becomes high (low) after some delay in time (1 qualitative time is consumed as defined later). The sign of the phase lag plays a central role to discriminate dynamic behavior as discussed in the next subsection.

Even though the quantitative information of the coefficients of the mathematical model are difficult to obtain, this qualitative information for each interaction is readily obtainable for most dynamical systems.

The above qualitative model can includes process fault by adding external disturbance nodes to a qualitative model describing the behavior of the system. Several types of faults are shown for the buffer tank example in Figure 2. Some of the faults listed in Table 2 can be expressed as additional nodes affecting the other nodes on the qualitative model. Other process faults in their extreme cases may change the structure of the graph. For example, complete blockage of exit line not only makes F2 low but disables the two arcs directed to F2. Such disabling effects are shown in broken line in Figure 2.

Global Analysis on The Model

Some of the global properties such as stability of the system does not come from the local propagation. This subsection describes some topological structures which are related to the global properties of the system. Some typical structures which is used for the global analysis are enumerated below. Here, circuit is a closed path where path is a graph connecting many nodes by the arcs of the same direction sequentially. The sign of a circuit is multiplication of all the signs of the arcs included in the circuit. The phase lag of the circuit is the summation of all the phase lag of arcs included in the circuit. The structure of the graph is assumed not to change its structure in the next subsection.

Negative circuit with phase lag 0: The model should not include this system. If the model includes the circuit, any disturbance to the variable within the circuit will make the opposite force to the variable simultaneously and thereby makes the conflict at the variable.

Circuit with phase lag 1: This system does not have any oscillation mode. The system will eventually converge (diverge) when the sign of the circuit is negative (positive). The model may have an oscillation mode only when it has negative circuit with phase lag more than 2.

Negative circuit with phase lag 2: The model including this system may have an oscillation mode. In some special cases [5], the oscillation can be determined whether stable or not only by the qualitative information of sign structure. In most of the cases, quantitative information of the strength of the effects is needed to determine the stability.

Circuit with phase lag more than 3: If the model includes this system, stability cannot be determined by the qualitative information. Quantitative information of the strength of the effects is always needed to determine the stability [5].

Reconvergent fanout paths of different sign and of the same phase lag: In this case, the qualitative value of the end variable of the fanout paths cannot be determined due to the conflicting effects from these two paths.

QUALITATIVE SIMULATION

Preliminaries

State of Variable: Each dynamical variable has several derivatives: 0-th order derivative (the state itself), 1st order derivative (velocity), 2nd order derivative (acceleration) and so on. The state of a variable can be specified by giving a qualitative value to all the derivatives of the variable.

Transient State: Transient state (as opposed to stationary state) of a variable is defined as the state that some level of the state will be changed
because of the non-zero of the higher derivatives. For example, \( L_1 = \text{normal} \), \( \frac{dL_1}{dt} > 0 \) is the transient state, since \( L_1 \) will be \( \text{High} \) in some lag time.

Qualitative Time: Qualitative time (q-time) is incremented by one whenever the dynamic change (see next subsection) has been done. In other words, it is incremented by the integer 1 when \( (m+1) \)-th derivative of a variable affected \( m \)-th derivative in the variable of transient state.

Algorithm for Qualitative Simulation on the Model

The qualitative simulation is carried out by iteration of the following cycles.

1. Static Propagation: If any (not necessarily one) of the variable is disturbed, then it (they) is propagated to all the other variables connected by the arcs. The qualitative value of \( n \)-th order derivative is changed if the variable is connected by \( n \)-th order lag 1arc \( (n,+) \) or \( (n,-) \).

2. Dynamic Change: If there is a variable of transient state, then the variable must be made stationary by changing the qualitative value of lower order derivative. After all the dynamic change have done, qualitative time is incremented by one. If any static propagation is possible, the system goes back to (1)

If there are many dynamic changes possible in many variables at the same qualitative time, we make all the dynamic change in the same qualitative time. We call this version of qualitative simulation synchronous version.

Generation of Diagnostic Rules by Qualitative Simulation

We use the qualitative simulation to generate the syndrome-fault associations for on-line diagnosis. Simulation is done by first inserting process fault as the external disturbance to the qualitative model. And then, propagating the effect through the model.

Using this qualitative model, most of the rules in Table 1 are automatically generated by a qualitative simulation. This method of generating the diagnostic knowledge for syndrome-based diagnosis is similar to the disturbance analysis often used in fault analysis of dynamical systems except that the simulation is carried out on the qualitative model.

As an example of a qualitative simulation, consequence of fault (2) (a leak between \( F_2 \) and \( V_1 \)) are shown in Table 4 with q-time shown in the left most column. Table 4 illustrates how rules 16 and 18 in the Table 1 are generated. In this qualitative simulation the propagation of the disturbance is stopped because all the variables are in stationary state. The cancellation occurs at q-time 1 because the negative feedback includes only first order lag. If the system includes negative feedback of more than second order lag, oscillation or divergence may occur depending on the sign structure of the graph.

Limitations of the Qualitative Simulation

Through the experiences of using AQUA, we have identified several ambiguities of qualitative simulation in terms of generation of diagnostic rules.

1. The qualitative simulation cannot discriminate the global properties such that the oscillation may decrease, increase or just periodical.

2. The qualitative simulation cannot determine the state of the variable when there are conflicting effects to the variable.

3. Several types of ambiguities about the time.

Suppose the interaction from \( L_1 \) to \( V_1 \) has the 1st order lag in the buffer tank example. (i.e. the valve movement has delay) Suppose also that the interaction from \( L_1 \) to \( F_2 \) is negligible relative to other interactions. In this case, the qualitative simulation shows that \( L_1 \) and \( V_1 \) oscillates. However, it is not known the oscillation eventually converges or diverges. This is because the qualitative simulation depends on the local propagation. We avoid this problem by integrating the method for analyzing the global properties such as qualitative stability on the qualitative model. However, there still remains the cases when the global properties cannot be discriminated. This is the cost of not using the quantitative values.

The situation of 2 happens, for example, when double faults (4) and (5) occurred where these events have the conflicting effect on \( \Delta F \). This situation has often happened even in single fault in more complex examples. Our two strategies for this problem are: First, we do not obtain long (along the time) evolution of the syndrome for the fault. Rather we obtain the above for the purpose of on-line real time diagnosis. Second, even when the ambiguous state occurred in simulation, AQUA will assign the qualitative value if it is available from the experts. And then continue the simulation. AQUA's model have the parameter indicating the strength of the interaction. The parameter of the dominating effect is set higher than those of others, although the parameters of all the interaction are set to 0 (default value) initially. This is also the way that AQUA facilitates interactive transfer of knowledge. If the expert cannot specify the state, AQUA can split the case, and continue the simulation for each case. Interestingly, expert can often tell what qualitative value some variable will eventually converge even though they cannot tell the state transition before the final value. In AQUA, such

<table>
<thead>
<tr>
<th>q-time</th>
<th>L1</th>
<th>F2</th>
<th>V1</th>
<th>F1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>normal</td>
<td>high</td>
<td>normal</td>
<td>normal</td>
</tr>
<tr>
<td>0</td>
<td>decreasing</td>
<td>high</td>
<td>normal</td>
<td>normal</td>
</tr>
<tr>
<td>1</td>
<td>low</td>
<td>decreasing</td>
<td>high</td>
<td>normal</td>
</tr>
<tr>
<td>1</td>
<td>low</td>
<td>normal</td>
<td>closed</td>
<td>normal</td>
</tr>
<tr>
<td></td>
<td>low</td>
<td>normal</td>
<td>closed</td>
<td>normal</td>
</tr>
</tbody>
</table>

Table 4: A Qualitative Simulation for the Leakage between \( F_2 \) and \( V_1 \) in the Buffer Tank Example
heuristics are also acquired from the expert.

As for the problem 3, AQUA's model has two other parameters to differentiate the delay other than the parameter indicating the phase lag. The first parameter indicates the order of the lag time. For example, two tanks are connected by the long pipe, in cascade then the disturbance in the outlet of the first tank is propagated to the inflow of the second tank with lag time. In that case, the expert sets the parameter in appropriate level, or AQUA does so through the interactive session with the experts. The second parameter indicates the speed of the dynamic change. When variables A and B are in the state of normal and increasing in the same q-time, AQUA will make both of them high in the next q-time (synchronous simulation). However, A might become high in order to generate a qualitative del for the other component in what way rather than carefully tuning these parameters.

Further, the diagnostic rules generated are only applicable as the event occurred when the target system is in stationary operation mode, since the simulation is carried out by inserting the disturbance to the stationary state. In other words, other method should be used to generate the diagnostic rules for transient operation mode such as start up phase or shut down phase.

**MODEL BUILDING AND REFINEMENT**

So far, we have discussed a way that AQUA facilitates knowledge acquisition in rule generation phase: the rules for syndrome-based diagnosis can be generated automatically. Although building model is easier than constructing diagnostic rules directly, the model building task still remains. In this section, we discuss the way for building the qualitative model systematically, and thereby facilitates the knowledge acquisition process in model building phase.

In model building phase, there are two ways that AQUA facilitates knowledge acquisition. First, by separating plant-common knowledge from plant-specific knowledge, much of the same knowledge can be used for different process plants. This will be discussed in the next subsection. Secondly, qualitative simulation and qualitative diagnosis can be used in conjunction to locate inadequacies in the model or rules. This will be discussed in the second subsection.

**Building the Qualitative Model**

In order to generate a qualitative model for a process plant, template models must be prepared for the components which commonly appear in the plant such as valves and heat exchanger. Then these template models will be connected to obtain the whole model for the plant. The knowledge needed to generate the model can be divided into two kinds:

1. **Plant-common knowledge:**
   - generic knowledge for plant-common component --- template model for a component in a instrumentation system, what types of fault the component may have, and the fault is expressed in what way in terms of disturbance to the related flows.
   - generic knowledge about the properties of flows --- what types of dynamics the flows obey, and the effects of disturbance to the flows, and
   - plant-specific knowledge: structural knowledge about the geometrical assignment of components and flows.

The plant-specific knowledge can be obtained from design data such as PFD (process flow diagram) of a process plant. By expressing these two types of knowledge separately, the qualitative model can be generated, for other types of plants by replacing only the plant-specific structural knowledge. This feature can enhance productivity in building knowledge bases.

As a knowledge expression, the frame is used for each component. Each frame has the following slots:
1. The name of the component.
2. The name of the super class component.
3. Variables (Variables are defined as an attribute of the flow.)
4. Relations (dynamic relations among variables, disabling and activating relations between variable and relation).

The plant-specific knowledge must also include the following information:
1. Topology about flows and components.
2. Boundary conditions for connecting components, i.e. which variable of a component is connected to which variable of the other component in what way.

For example, a qualitative model for diagnosis of the buffer tank (Figure 2) can be generated from generic knowledge and structural knowledge. A part of that knowledge needed to build the total model of the buffer tank example is presented in the appendix.

**Refinement of the Qualitative Model**

After the model is generated, refinement is done in two levels: the qualitative model level and the rule (syndrome-fault association) level. More importance is placed on the modification at the model level, since the model has the great impact on rules. Refinement is done during the validation process. AQUA used the following two methods for validating the model:

**Qualitative simulation is carried out for test case faults.** If the results (syndrome) are unsatisfactory, then the expert provides the system with the expected results.

Model-based diagnosis (not discussed in this paper) on the qualitative model is carried out for test cases. If the results (faults) are unsatisfactory, then the expert provides the system with the expected faults.

By these two sessions, the model will be interactively modified, and thereby the knowledge of the expert will be transferred. The qualitative model is modified by changing the attribute of the arc such as, the order of phase lag and sign or by changing the structure of the model.
(deletion/addition of arcs and nodes). The attribute change of the arcs is first tried and if it fails to cover the modification, the structural change is done.

CONCLUSION

Knowledge acquisition tool in process diagnosis domain is discussed. First, a prototype of a qualitative model is built. Then the qualitative model is refined interactively by the experts, allowing the knowledge transfer from experts. A qualitative model is used for generating and refining diagnostic rules.

It is shown that the most of the diagnostic rules for syndrome-based diagnosis can be made by the qualitative simulation on the qualitative model. Although we have developed the method for doing model-based diagnosis directly on the qualitative model, this method of qualitative model is discussed elsewhere.

Through many interviews with process diagnosis expert, it is known that our qualitative model is adequate for acquiring knowledge of process dynamics. However, we always face the problem of integrating the quantitative information partially into the qualitative semantics, since the experts always use both of them. In this stage of our project, we only use quantitative values for checking these values by the quantitative equations. This problem is left for the future research.

REFERENCES


I. Assignment of components:

instance: pipe1:
  super: pipe;
  liquid-flow-connection-cascade:
  tank;
end;
instance: tank1:
  super: tank;
  liquid-flow-connection-bottom-feed:
  pipe2;
  signal-connection:
  valve1(signal);
end;
instance: valve1:
  super: control_valve;
  flow-control:
  pipe2;
end;
instance: pipe2:
  super: pipe;
end.

APPENDICES

I. A part of a data base of the component model:

class: flow;
variables:
inflow: in(flow) , triple(high,normal,low);
outflow: out(flow) , triple(high,normal,low);
end;
class: flow_with_accumulation;
super: flow;
variables:
inflow: variable, triple(high,normal,low);
level: out(signal);
relation:
re1: inflow<-(O,->) inflow;
re2: inflow<-(O,-) outflow;
re3: level<-(1,+) netflow;
re4: outflow<-(0,+): level;
end;
class: tank;
super: flow_with_accumulation;
variables:
leak@tank: disturbance , binary(fault, normal);
relation:
re1: netflow<-(0,-): leak@tank;
end;
class: pipe;
super: flow;
variables:
leak@pipe: disturbance , binary(fault, normal);
complete, leak@pipe; fault, binary(fault, normal);
complete, block@pipe: fault, binary(fault, normal);
relation:
re1: outflow<-(0,+): inflow;
re2: inflow<-(0,+): leak@pipe;
re3: inflow<-(0,-): block@pipe;
re4: rel<disable: complete, leak@pipe;
re5: rel<disable: complete, block@pipe;
end;
class: valve;
super: flow;
variables:
shaft_position: triple(open,normal,close);
stick: fault, binary(fault, normal);
relation:
re1: outflow<-(0,+): shaft_position, inflow;
re2: rel<disable: stick;
end;
class: control_valve;
super: valve;
variables:
set_position: in(signal) , triple(open,normal,close);
relation:
re1: shaft_position<-(0,+): set_position;
end;