Fault Detection for A Variable Air Volume System By Stochastic Qualitative Reasoning

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Abstract: This paper presents a fault detection method for a Variable Air Volume (VAV) system by means of stochastic qualitative reasoning. The VAV system, which is a building air conditioning system, controls the temperature and the volume of supplied air in the refrigerator and in the VAV valves for air conditioning. In order to ensure that the system is operating properly, it is necessary to detect the malfunctions in it from the perspective of the indoor environment. However, the various and changeable structure of each air conditioning system makes it difficult to formulate the physical relationships between its factors. In addition, because of cost concerns, the numerical information that is measured by sensors of limited numbers is not enough to detect problems in a complex system of that type. The goal of this study is to detect faults in this kind of system by means of the stochastic qualitative reasoning method. In this method, the complex structure of the VAV system can be expressed by a qualitative model. On the basis of the qualitative models that correspond to normal and abnormal operation, the behaviors of the system are analyzed in order to pinpoint the cause of the faults.

Keywords: Fault detection, Qualitative reasoning, Qualitative model, Building air conditioning system, Simulation

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1. Introduction

The variable air volume (VAV) system is an air conditioning system for buildings. In this system, supplied air temperature is controlled at set-up values and the air is sent to all areas of the target room. By controlling the volume of the supplied air, the room temperature can be adjusted according to the set-up value. In order to prevent the system from negatively impacting upon the indoor environment and to protect against unexpected accidents, it is necessary to have the ability of detecting its faults.

One useful approach to effective fault detection of systems that are in operation is model-based reasoning. In this approach, a model that represents the structures and functions of a target system is built in advance, and possible behaviors are derived. By comparing the virtual behaviors based on each of the models (i.e. fault models and a normal model), with the observed real behavior of the target, a fault part can be identified. However, it is difficult to construct precise models of complicated and vague targets, such as VAV systems. In addition, because of a limited number of sensors, it is impossible to acquire sufficient data for fault detection.

Qualitative reasoning [1] is useful with respect to the fault detection of this kind of a system [2,3]. The advantage of the above is that a model can be simulated without complicated functions. In this approach, the system is described by a qualitative model that is composed of only abstracted factors and their causal relationships. However, this approach multiplies the possible behavior patterns that are specified with a series of states of the model significantly because of the ambiguity of qualitative reasoning.

We have developed the stochastic qualitative reasoning method in order to cope with intractable states [4,5,6]. In this method, the concept of existence probability is introduced to each state that is derived from the model. Consequently, an explosive increase in the number of states is effectively prevented by pruning off those states with relatively small probabilities. In addition, by means of existence probability, the agreement rate (which is a parameter that shows how the behaviors that are derived from the reasoning reflect the actual system), can be calculated. On the basis of this parameter, more than one candidate can be ranked in order of the possibility of faults.

In this paper, we applied this method to fault detection of a VAV system in a building in Tokyo. Using the field data, we attempted to detect several malfunctions. In the next Section we will give an outline of the VAV system. In Section 3 we will show how to construct a qualitative model of the system. Section 4 presents the stochastic qualitative reasoning method, and Section 5 demonstrates the fault detection of a VAV system by stochastic qualitative reasoning and shows how a fault point can be detected by using simulation results.

2. An Outline of A Variable Air Volume System

Figure 1 gives an outline of the variable air volume (VAV) system of the building in Tokyo that we analyzed. This system consisted of 1 fan, 1 refrigerator, 8 VAV valves and sensors.

This system controls the room air temperature by supplied air temperature and room air volume. With the fan and refrigerator, supplied air is generated from outside air, and is separated in order to send it to each VAV valve. At each valve, the air volume is controlled according to the room temperature gap between the set-up value and the measured one. The room air volume controls the room air temperature.

The following factors are important in order to trace the behavior of the system.

Full Open Signal

The full open signal shows whether more than one VAV valve has been opened fully.

Supplied Air Volume

Supplied air volume is controlled according to the behavior of the fan. If the full open signal is 'on', it will increase because there is sufficient room air volume.

Supplied Air Temperature

Supplied air temperature is controlled by the volume of the cold water in the refrigerator. The real supplied air temperature follows its set-up value under normal conditions.

Room Air Volume

The supplied air volume and the degree of opening of the VAV valve determine the room air volume. The room air volume is controlled by the measured room temperature according to the set-up value of room temperature.

Room Air Temperature

Room air temperature is determined by the volume of room air, whose temperature is the same as that of the supplied air.

Heat Resource

The heat resource shows disturbances to the heat load such as OA-machines and humans. It disturbs the temperature of a room.

The set of conditions for each factor represents the state of the target VAV system. These factors (except for "heat resource") are observed with sensors and the measured data are recorded for every one unit of time, which is defined as 5 minutes in this system. The delay of propagation to observe data from the measured point by these sensors can be defined as one unit of time.

The components of the system can influence the condition of factors. The VAV system has the following components:

Fan

For the generation of supplied air, open air is introduced by the fan. In this component, the supplied air volume is controlled by the full open signal.

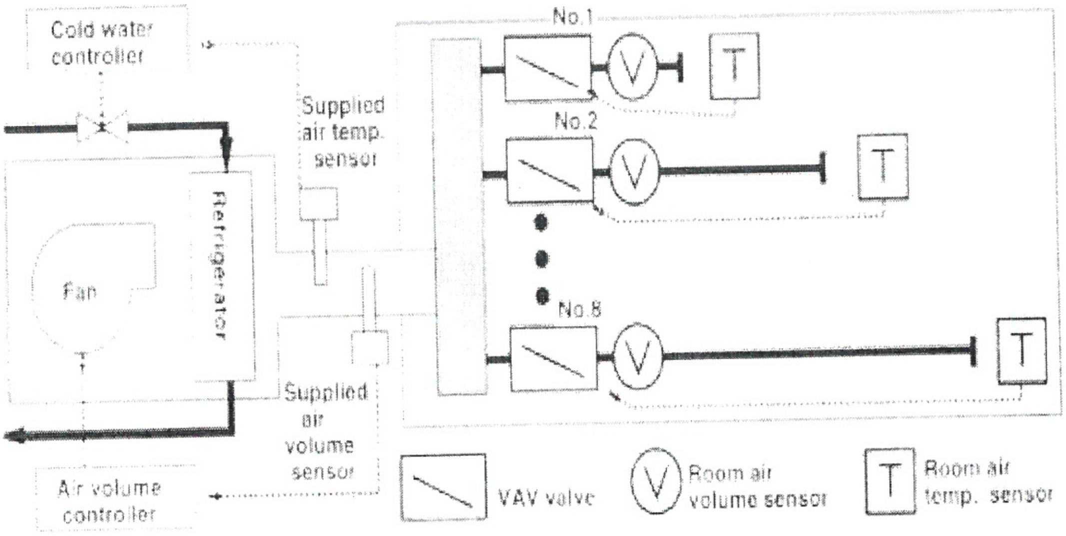

Figure 1. An Outline of A Variable Air Volume System

Refrigerator

The supplied air is cooled in the refrigerator. The air temperature is determined by the volume of cold water in it.

VAV Valve

Each VAV valve can control the supplied air volume for each area of the room according to the gap between the set-up room temperature and the measured room temperature.

Room Air

As a result of VAV volume control, the room temperature in each area of the room is determined according to the room air volume and the supplied air temperature.

Disturbance

This component shows the disturbance of room air temperature to the heat load as OA-machines and humans. It reflects an uncertain behavior in the system.

A component can also be regarded as a causal relationship among the elements in the physical relationship of the system. That is, a component receives information about the conditions of certain factors and orders a change in a factor. For example, the VAV valve receives supplied air volume, measured room air temperature and supplied air volume, and orders a change in the room air volume.

3. Qualitative Model of A Variable Air Volume System

3.1 Qualitative Model

A qualitative model is used to model a target system with only the essential factors and their causal relationships. A qualitative model of a VAV system under normal conditions is shown in Figure 2. The qualitative model consists of nodes, arcs and functions, which will be explained in detail, respectively as follows.

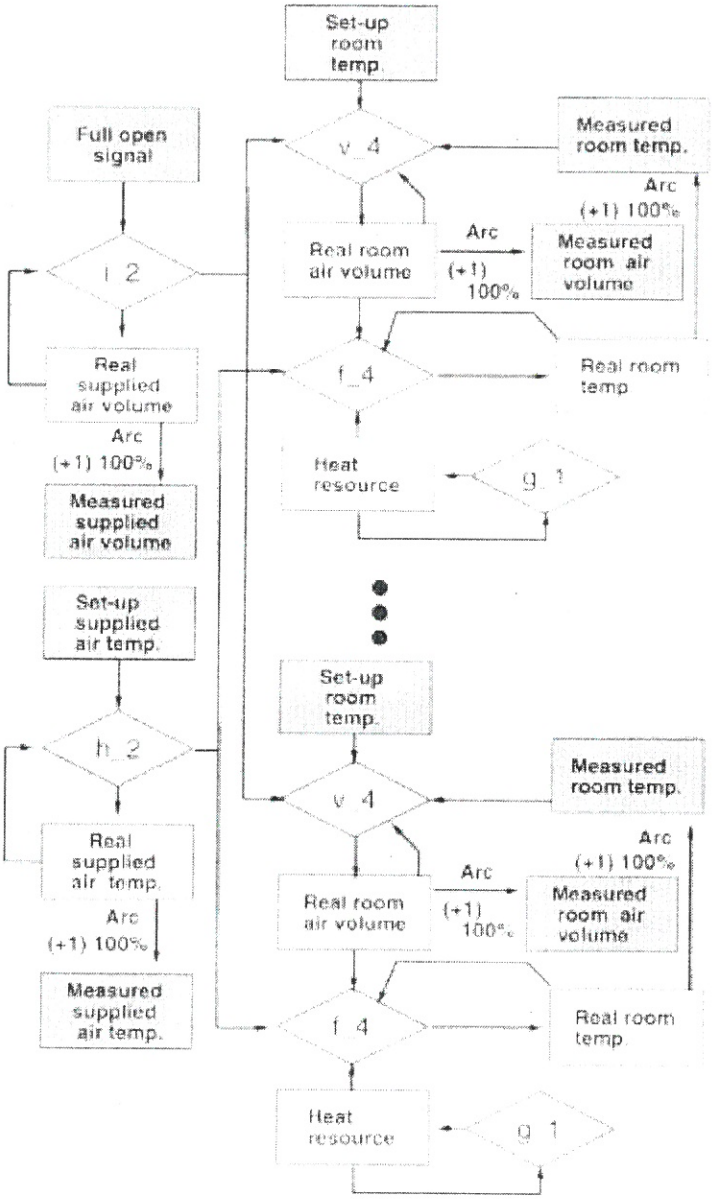

Figure 2. A qualitative model of a VAV system

Node

A node represents the elements in the target system. In the VAV system, for example, factors such as the supplied air temperature and room air volume are defined as nodes. Each node is characterized by certain qualitative values such as those in Table 1, in order to represent the condition.

Table 1. An Example of Qualitative Values

Qualitative value	Interpretation	Definition
A	extremely hot	21° C ~
B	hot	17° C ~21° C
C	normal	13° C ~17° C
D	cold	9° C ~13° C
E	extremely cold	~ 9° C

In Figure 2, the factors of the target system (see Section 2) are defined as nodes. The set of qualitative values of these nodes shows the state of the target system. The node that represents a factor which can be measured by a sensor is called a *measured node*. The nodes with a stitch pattern in Figure 2 are the measured ones.

Arc and Propagation Rules

In a building air conditioning system similar to a VAV system, a sensor can be represented by an arc.

An arc with attached propagation rules connects two nodes. The arrow of the arc shows the direction of influence propagation. The propagation rule includes the type of influence, time lag, and the probability of choosing this rule. The five types of propagation rules are shown in Table 2.

Table 2. Types of Propagation Rules

+2(-2)	If the source node of the arc changes, the destination node changes in the same (opposite) manner of the source node two time units later
+1(-1)	If the source node of the arc changes, the destination node changes in the same (opposite) manner as the source node one time unit later.
std	If the source node of the arc changes, the destination node keeps still unchanged

More than one propagation rule is often attached to an arc. In this case, each rule has a choosing probability which indicates the probability of the rule being applied.

In a VAV system, all propagation rules can be defined as (+1) 100% from the properties of the sensors.

Function

A component of a system like a VAV valve can be expressed by a function. In causal relationships that are expressed by a function, a qualitative value of a destination node is influenced by the qualitative values in the source node. For example, in relationships that are expressed by a VAV valve, the room air volume is influenced by the supplied air volume, the set-up and the measured room temperatures, and the room air volume for the last unit of time.

A function receives qualitative values of nodes as inputs, and orders changes and gives their probabilities as output. Three types of changes as regards a function are shown in Table 3. Table 4 shows an example of definition of a function. Each change of the source node is determined according to the Table.

Table 3. Types of Changes in A Function

Up	The destination node value increases
Down	The destination node value decreases
Const.	The destination node value is unchanged

Table 4. An Example of A Definition of A Function

Input	**Output**		
Set	**Prob.(%)**		
Temp.	**Up**	**Const.**	**Down**
A	0	60	40
B	0	80	20
C	10	80	10
D	20	80	0
E	40	60	0

The functions in Figure 2 correspond to the components of the system in Figure 1. Table 5 shows the relationship between the functions and the components.

Table 5. The Relationship Between Functions and Components

Function	**component**
*g*_1	Disturbance
*l*_2	Fan
*h*_2	Refrigerator
*v*_4	VAV valve
*F*_4	Room

4. Stochastic Qualitative Reasoning

4.1 Reasoning Algorithm

Stochastic qualitative reasoning can effectively analyze the behaviors of a complex system. The reasoning progresses with the transition of states, which can be defined as a set of qualitative values of all nodes in its qualitative model. A series of state transitions shows the system's behaviors.

In stochastic qualitative reasoning, the threshold is used to eliminate states with small probability. The stochastic qualitative reasoning procedure will be briefly explained as follows [4,6]: here, the existence probability of the initial state has been assumed to be 1.0.

Step 1: Predict all possible states from current states according to the function and propagation rules, and obtain each existence probability.

Step 2: Rank the states in descending order of existence probability. Add all the existence probabilities until the sum amounts to the threshold. Then eliminate all remaining ones.

Step 3: Compare the surviving states with the real measured values. Eliminate the inconsistent ones.

Step 4: Normalize the existence probabilities of the surviving states. These states will act as the current states at the next stage. Repeat all steps until there are no surviving states or all of the stages are finished.

By eliminating states with small probabilities at Step 2, the number of generated states can be limited.

4.2 Agreement Rate

Stochastic qualitative reasoning can evaluate how the model reflects an actual system. The reasoning result can be obtained in the form of a simple parameter, which we have termed with the agreement rate of the model under observation.

It is defined as follows:

$$R = \left(\frac{\hat{P}_1}{P_1} \times \frac{\hat{P}_2}{P_2} \times \ldots \times \frac{\hat{P}_n}{P_n} \right)^{\frac{1}{n}} ,$$

where P_i is the sum of the existence probabilities of states that have survived at Step 2 and $\hat{P}_i$ is the sum of the existence probabilities of the states after removing those that are inconsistent with the measured values at Step 3. n is the total number of times that the simulation is performed.

If there are no surviving states, the agreement rate is calculated as zero and the simulation is terminated.

5. Fault Detection of A VAV System by Stochastic Qualitative Reasoning

5.1 Fault Detection By Means of Stochastic Qualitative Reasoning

The fault detection method is shown in Figure 3. The normal model is a qualitative model of a system under normal conditions. It is based on a target system instrumentation diagram and human qualitative considerations. By modifying the functions or arc propagation rules that correspond to each assumed malfunctioning part, several fault models can be constructed. The behaviors that are derived from the stochastic qualitative reasoning with every qualitative model are compared with the observations so that the faulty parts can be detected.

5.2 The Qualitative Models of A VAV System Under Abnormal Conditions

Qualitative models that represent every assumed fault were built by modifying the normal model shown in Figure 2. These assumed faults are as follows:

- Fault model: "VAV valve full open"
  - Phenomenon: VAV valve is fixed with full open condition
  - Modification: Function "v_4" is modified in order to lower the temperature of a room
- Fault model: "VAV valve full close"
  - Phenomenon: VAV valve is fixed with full close condition
  - Modification: Function "v_4" is modified in order to raise the temperature of a room
- Fault model: "Supplied air volume decrease"
  - Phenomenon: Supplied air for a fan is decreased

  - Modification: Function "i_2" is modified in order to raise the temperature of a room

- Fault model: "Cold water volume decrease"
  - Phenomenon: Cold water in the refrigerator is decreased
  - Modification: Function "h_2" is modified in order to raise the temperature of a room

Table 6 shows the definition of the qualitative values for fault detection.

5.3 Fault Detection Result

As regards the target VAV system of a building in Tokyo, we performed the experiments on fault detection on August 7 and November12, 1996. For each experiment, we assumed the existence of four intentional faults.

Table 7 shows the time that each fault occurred on August 7 and November 12. In this Table, the faults "VAV valve full open" and "VAV valve full close" occurred at VAV valve No.6.

Table 6. The Definition of Qualitative Values for A VAV System

Qualitative value	Temp. of supplied air (°C)	Temp. of room air (°C)	Volume of supplied air (m^3/h)	Volume of room air (m^3/h)	Full open signal
A	21 ~	27.5~	5000 ~	1700 ~	on
B	17 ~ 21	26.5 ~ 27.5	3500 ~ 5000	1200 ~ 1700	off
C	13 ~ 17	25.5 ~ 26.5	2000 ~ 3500	700 ~ 1200	–
D	9 ~ 13	24.5 ~ 25.5	500 ~ 2000	200 ~ 700	–
E	~ 9	~ 24.5	~ 500	~ 200	

Table 7. Time Each Fault Occurred

fault	August 7	November 12
normal	9:00 ~ 9:30	9:00 ~ 9:30
VAV valve full open	10:15 ~ 10:45	10:00 ~ 10:30
VAV valve full close	11:30 ~ 12:00	11:20 ~ 11:50
supplied air volume decrease	14:05 ~ 14:35	13:35 ~ 14:05
cold water volume decrease	15:25 ~ 15:55	15:35 ~ 16:05

We applied these field data to fault detection using the stochastic qualitative reasoning.

At first, the four qualitative models (VAV valve full open, VAV valve full close, Supplied air volume decrease, Cold water volume decrease) that represented each fault were built based on this normal model, as mentioned in the previous Section.

However, these models only have three VAV valves (No.5, No.6, and No.7), because they are large enough in scale to represent behaviors in the fault condition. Next, the behaviors of each model were derived by stochastic qualitative reasoning individually with a threshold of 0.5 and a time period of 6 units (a unit of time is defined as 5 minutes).

The agreement rates of all fault models with the measured values are summarized in Tables 8 and 9. The average calculation time of the stochastic qualitative reasoning for an agreement rate was about 10 minutes.

Tables 8 and 9 show that the stochastic qualitative reasoning was effective in identifying the causes of the faults. The faults in the two seasons (summer and autumn), were detected with a common model and a common definition of qualitative values. These results clarify on the fact that stochastic qualitative reasoning with vague qualitative models has robustness with respect to tracing the behaviors in a complicated target system with various measurement data.

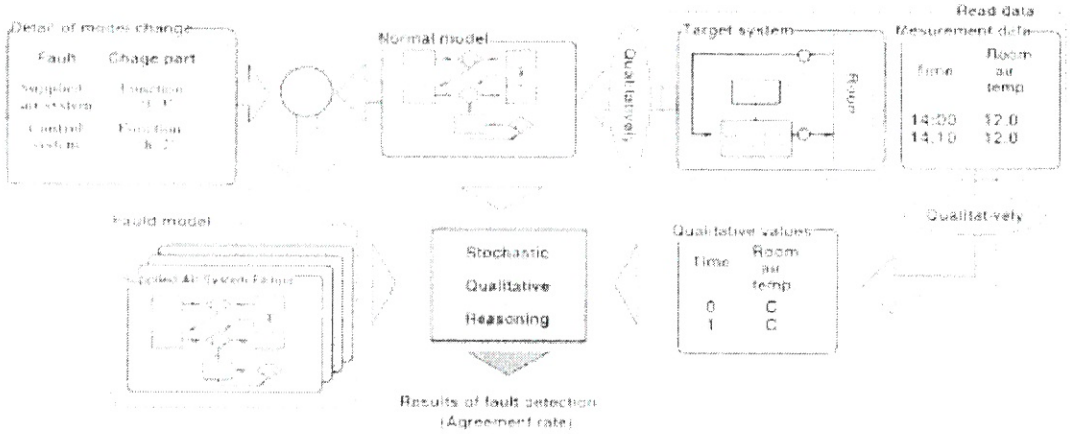

Figure 3. Fault detection by stochastic qualitative reasoning

Table 8. Fault Detection With A Model Generated on August 7

fault situation	fault model				
	normal	VAV valve full open	VAV valve full close	supplied air volume decrease	cold water volume decrease
normal	**0.00741**	0.00000	0.000	0.00192	0.00000
VAV valve full open	0.0187	**0.00236**	0.00000	0.00000	0.00000
VAV valve full close	0.00000	0.00000	**0.00425**	0.00000	0.00000
supplied air volume decrease	0.00000	0.00000	0.00000	**0.00168**	0.00000
cold water volume decrease	0.00000	0.00000	0.00000	0.00000	**0.00236**

Table 9. Fault Detection With A Model Generated on November 12

fault situation	Fault model				
	normal	VAV valve full open	VAV valve full close	supplied air volume decrease	cold water volume decrease
normal	**0.00223**	0.00038	0.000	0.00223	0.00025
VAV valve full open	0.00000	**0.00615**	0.00000	0.00000	0.00000
VAV valve full close	0.00261	0.00000	**0.00567**	0.00256	0.00000
supplied air volume decrease	0.00000	0.00000	0.00000	**0.03074**	0.00000
cold water volume decrease	0.00000	0.00000	0.00000	0.00000	**0.00414**

6. Conclusion

In this paper we applied the stochastic qualitative reasoning method to fault detection of a Variable Air Volume (VAV) system. In this method, a complex system in two seasons was simulated by means of simple common qualitative models.

Our results demonstrated the effectiveness of stochastic qualitative reasoning in the detection of VAV system malfunctions. In addition, we confirmed the following properties of stochastic qualitative reasoning in the above fault detection.

- Stochastic qualitative reasoning has robustness for tracing the behaviors in a complicated target system with various measurement data.
- Stochastic qualitative reasoning can perform real-time simulations of large air conditioning systems by limiting the number of generated states, using the stochastic elimination.
- Different types of elements (temperature and air volume), can be connected by the causal relationship `function' in the qualitative model.

Unfortunately, this method has an unavoidable drawback: model generation is quite difficult. Since a qualitative model has many stochastic parameters such as functions and arc propagation rules, to determine the probability of these stochastic parameters is a difficult problem. It requires extensive knowledge about the system being examined. Moreover, whether the determined probability is proper or not has a great effect on the reasoning results. Our research group currently develops an approach to automatic model generation for stochastic reasoning [7]. In this approach, the function and arc propagation rules are formalized with several characteristic parameters which represent the regular relationships among these stochastic parameters. A proper model can be generated by tuning these characteristic parameters.

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