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Process Fault Diagnostics Using the Integrated Graph Model

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ABSTRACT

On-line fault detection and diagnosis has an increasing interest in a chemical process industry, especially for a process control and automation. The chemical process needs an intelligent operation-aided workstation which can do such tasks as process monitoring, fault detection, fault diagnosis and action guidance in semiautomatic mode. These tasks can increase the performance of a process operation and give merits in economics, safety and reliability.

Aiming these tasks, series of researches have been done in our lab. Main results from these researches are building appropriate knowledge representation models and a diagnosis mechanism for fault detection and diagnosis in a chemical process.

The knowledge representation schemes developed in our previous research, the symptom tree model and the fault-consequence digraph, showed the effectiveness and the usefulness in a real-time application of the process diagnosis, especially in large and complex plants. However in our previous approach, the diagnosis speed is its demerit in spite of its merits of high resolution, mainly due to using two knowledge models complementarily.

In our current study, new knowledge representation scheme is developed which integrates the previous two knowledge models, the symptom tree and the fault-consequence digraph, into one. This new model is constructed using a material balance, energy balance, momentum balance and equipment constraints. Controller related constraints are included in this new model, which possesses merits of the two previous models. This new integrated model will be tested and verified by the real-time application in a BTX process or a crude unit process. The reliability and flexibility will be greatly enhanced compared to the previous model in spite of the low diagnosis speed. Nexpert Object for the expert system shell and SUN4 workstation for the hardware platform are used. TCP/IP for a communication protocol and interfacing to a dynamic simulator, SPEEDUP, for a dynamic data generation are being studied.

1. INTRODUCTION

The importance of a fault diagnosis and a safety assessment on a chemical process becomes serious according to the complexity, accuracy and automation of the chemical process. These are due to following factors :

- process complexity due to energy integration
- adoption of advanced process control system
- necessity for higher quality of products

However these changes of a chemical process can induce a timid fault into a hazardous event and also drives the product quality varying according to the process variation. A brief introduction to the safety assessment and the fault diagnosis will be given.

Main development of a theory and experience on the safety assessment were done after the large disaster from chemical industry. Originally the safety assessment method like falut tree analysis was adopted in the analysis of safety of the missile system. After the successful application, nuclear power plant became a next application area and the result was also good. Practically nuclear power plant has the similar equipment and instrument compared to a chemical process, especially heat exchanger network and pump. However the application of the fault tree method to the assessment of a chemical process safety was late compared to the above two areas. These are due to the following reasons :

- difficulties in modelling the chemical process
- lack of fund and support from government or company

The difficulties in modelling the chemical process is come from a heterogeneosity of the equipments, multi-valued state of the process variables, complex chemical reaction mechanisms, and the use of advanced process control systems. These factors make the modelling problem more difficult. The other factor was due to the trade-off between economics and needs on the research and application of the safety methodology.

However new motive and support were getting attention due to the changing characteristics of a chemical process. New idea and methodology were adopted and applied. Currently the construction of a fault tree remains some problems like adaptation to the nonmonotonic behavior of a process variable, the top-down characteristics, and the completeness of the knowledge itself.

The history of a fault diagnosis problem has two directions: one is quantitative approach and the other is a qualitative one. In quantitative approach, the system behavior can be modelled and the parameter estimation technique can give the solution of a fault detection problem. However in this case, the system size must be small and the rigorous description be available. So the application area becomes narrow.

The other approach , qualitative approach, was developed aiming the practical application in spite of the poor numerical model. Heuristic method and model-based method is main branches. Heuristic diagnosis system uses shallow knowledge like experiance and operating manual. Its merit is a diagnosis speed and demerit is a lack of consistency in managing the diagnosis knowledge.

Model-based approach uses tree-like or graph-like structure. Fault tree method and signed directed graph were dominant approaches among them. Some problems also arose in using these models. Main problem is a noncompleteness of the knowledge representation. The differences between these two models are the inference direction and the nature of inductive or deductive characteristics. Those models have inherently one way information flow characteristics. The need and motive for more effective representation model was arosed to cope with these lacks. Other motives for new model can be summarized as follows:

- Development of expert system theory and application
- Requested high quality of plant operator training
- Need for the accumulation and integration of knowledges
- Increase of operation tasks that plant operators face and computerization of process
- Increase of hazardous disaster probability due to the complex process
- Necessity of process control system that meet the high quality of products

In the first phase, a rule base approach was used for the development of diagnosis system. However the demerit in interviewing and inconsistency in building the diagnosis system arose. The needs for more systematic approach to build the diagnosis system and safety assessment system arise in this background.

Currently two main approaches are adopted building the diagnosis system and safety assessment system . One is using tree-like model and the other is graph-like model.

Review on the two areas, the safety assessment and the fault diagnosis on the chemical process, shows some similarities and differences. The similarity come from the structure of knowldege rerpresentation models like tree or graph structure. The differences are the application phase(in design phase or operation phase) and on-line real-time characteristis. However these differences become small according to the development of a computing power and the needs from the industry and society. In this respect, the needs for new knowledge representation models that can be used in both areas commonly, the safety assessment and the fault diagnosis exist. And the new knowldege model must be synthesized from the structured knowldege like P & ID, and operating manual.

The objective of a previous reasearch in our lab was building a real-time diagnostic expert system which can do the diagnosis task accurately in real-time mode. The knowledge model was composed of two schemes, a symptom tree model and a fault consequence digraph, and the inference mechanism was somewhat complex to utilize previous two knowledge models effectively.

In this study, new knowledge representation model and a diagnosis mechanism is under developing. The knowledge model is integrated from the previous two models and the diagnosis mechanism become more simple. These are done from the analysis of the two models(Symptom Tree and Fault Consequence Digraph), synthesis of two models, and integration of two models. The main theme of this paper is the synthesis of each knowldege models .

2. Symptom Tree Synthesis

2-1. Background

Symptom tree is a qualitative graph model which represents fault propagation, cause-and-effect relationship among symptoms and its causes, in a process plant. Symptom tree model is basically derived from a symptom-sub tree concept and a definition of a symptom variable, and constructed in terms of boolean logic expression like the fault tree. The difference between the symptom tree and the fault tree come from the nature of their top event. The top event of the fault tree usually represents the hazardous events in a system while that of the symptom tree represents the symptom variable to be measured. Applications using the symptom tree model in the practical application is shown in Table 1.

Process	Methods	Workers
Cement Calcination Process	symptom tree symptom-failure cause table	Han & Yoon[3]
Naphtha Furnace	symptom tree	Kim & Yoon[2]
Naphtha Furnace	symptom tree FCD	Oh, Yoon & Choi [6]

Table 1. Applications using the symptom tree

Symptom tree construction is generally a complicated task like the fault tree one. Manual construction of the tree can be extremely time consuming. In addition to the time involved, systematic methodology is needed and the possibility that the consistency is fail exists. Therefore, it is natural that computer-aided synthesis gets considerable attention. From early 70's to middle 80's, several methodologies for computer-aided fault tree synthesis have been proposed. Section 2-3 describes the methodologies.

2-2. The construction method of symptom tree

The method that Han et al[3] proposed is as follows. Firstly, fault tree for a target process is constructed, then dividing it to obtain the symptom tree. To speak in detail, the hazardous event is selected as a top event and all specified component failures and process variables deviation leading to top event is represented in one tree. Then, symptom tree is extracted from the fault tree whose sensor variables become the top events.

Kim et al[2] obtained the symptom tree by combining successively the symptom-sub tree which is obtained for each process variable deviation. The events which are inconsistent with a top event are removed. The events which is missed in the symptom-sub tree that represents local causality are added.

Oh et al[6] derived the symptom tree from the FCD which is explained in section 3. This method was proposed to maintain the integrity between symptom tree and FCD and reduce the efforts of constructing the symptom tree. As symptom tree was constructed without symptom-sub tree for unmeasured variables, mistake and cumbersome were reduced.

There are several problems in the above methods. The demerit exists in Han's approach that a large fault tree must be constructed to abtain the symptom tree. Oh's method which derives the symptom tree from the FCD is easier to be constructed, but it is cumbersome to construct FCD first. Kim's method needs systematic refinement. Computer-aided symptom tree synthesis would be possible using symptom tree concept and the methodology for the computer-aided fault tree synthesis.

2-3. Symptom Tree Synthesis

Since Fussel[4] initiated an automated construction of a fault tree for a electrical system with his Synthetic Tree Model, many studies have been done. One of the informations for fault tree synthesis for process plant is the description of the process. There are two approaches on the description of the process. First approach is centered around the component units. The unit model on local causality among process variables is represented in terms of mini-fault trees(Powers & Tomkins[11], Martin-Solis et al.[10]). Second, the process can be described laying stress on process flowsheet structure(Lapp & Powers[8], Shafaghi et al.[12]) In this approach, process is represented in terms of directed graph or reliabilty graph and process interaction and cause-and-effect relationship is obtained from this graph. Using these information, complete fault tree is built up by an algorithm.

In this study, a chemical process is decomposed into the component units and symtom trees are constructed automatically using the library of mini-fault tree and process topology with macroscopic causality.

The system is implemented using C language and NEXPERT OBJECT of Neuron Data Inc. in SUN4 workstation for interfacing to the research that will follow. The system consists of three parts. These are a library of process unit models, analysis of process topology, and symptom tree synthesis. The library of unit models is represented in terms of mini-fault tree and is stored in the form of NEXPERT OBJECT's object. After the analysis of process topology, the top events of symptom trees are identified. In the symptom tree synthesis part, complete symptom tree is constructed using the unit models and the results of anlaysis of process topology. Tree expansion is restricted using the boundary constraints(BC) and the top event or their ancestors which are inconsistent are removed from the tree by the consistency constraints(CC). In this part, object oriented programming technique is used. Overall strategy is shown in Figure 1.

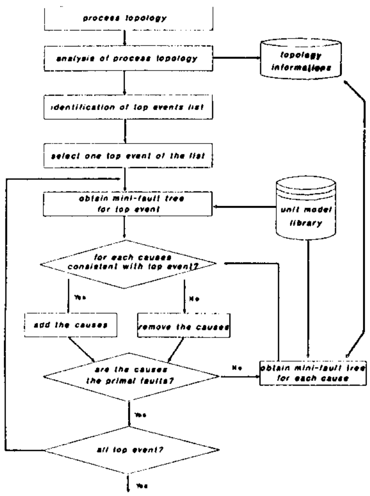

Figure 1. Overall Strategy for Computer-aided Symptom Tree Synthesis

2-4. Systematic construction of unit models

The process unit model is represented in terms of mini-fault tree which could be obtained from the following two methods.

The first, in the case it is difficult to obtain mathematical model, mini-fault tree is constructed using cause-and-effect relationship between variables obtained from operation data and experienced operators. The second, it can be obtained from mathematical model. The mathematical model usually consists of ordinary differential equations(ODE's) and algebraic equations(AE's). In general, ODE can be written in the form,

$$\frac{dxi}{dt} = fi(x1,\ x2,\ \ldots,\ xn)$$

The direction xj influences on xi is the sign of $\partial fi/\partial xj$. For example, for the process in Figure 2., the model equation for tank level is as follows.

$$dLt/dt = (Fi - Fo)/(D.A)$$

Because the sign of $\partial fi/\partial Fo$ is - , Fo influences on Lt in opposite direction. Therefore, outlet flow rate increases, Fo+, is the cause of tank level decrease, Lt-. Also, AE can be written in the form,

$$x_i = \sum_{j=1}^{n} a_{ij} x_j$$

The direction xj influences on xi is the sign of aij and the method of obtaining the mini-fault tree is identical with the above one.

2-5. Case Study

This program is illustrated for the simple process in Figure 2. This example process was used by Yoon, Han, and Kim. There exists four measured variables and a feedback control loop to control the level of tank. The outputs of this program is identical with the results of manual construction. The symptom tree whose top event is tank level decrease is shown in Figure 3.

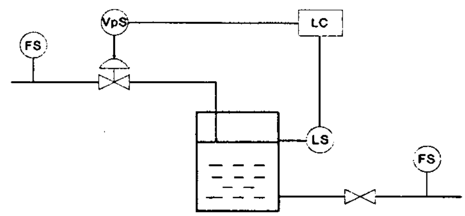

Figure 2. A Water Tank System

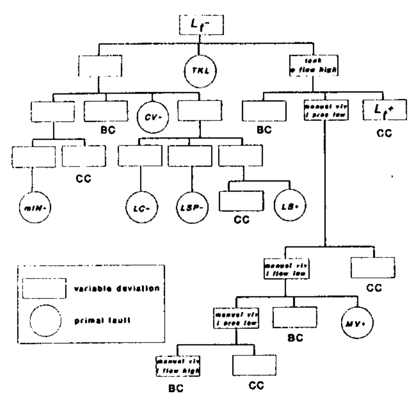

Figure 3. Symptom tree for tank level decrease, Lt-

From this study, we know the possibility that the symptom treemodel for process fault diagnosis can be generated automatically.

3.Automatic FCD construction

3-1. Background.

Fault-consequence digrah(FCD) is a typical bottom-up knowledge representation model. FCD represent the tendency of related variables with defined fault of the system. That is, it shows how the trend of the variable changes for some fault as time goes on. FCD have deep relation with qualitative simulation because of this deductive nature. Simulation describes how some inputs have effect on the variables of system for each time step. If this simulation-input means the some event of the system, the result of the simulation is the response pattern of the system naturally. The possibility of the automatic synthesis of FCD results from its relation with simulation. The properties and characteristics of FCD and the difference with SDG are shown as follows.

FCD is a qualitative model which represents the fault propagation pattern macroscopically. Fault or disturbance are propagted according to the cause-effect relation of the process variables in the system. The microscopic relation of the adjoined variables would be necessary condition for fault propagation, but is not sufficient for describing the path of tte fault propagation. In real world, there are many methods that the cause-effect relation is formed peculiary by the kind or state of the fault. And occured fault dominates the global fault propagation. FCD represent the fault and its propagation resting on the basis of these priciples deductively. According to the interpretation for whether the variable can be symptom or not in dynamic state, FCD include that variable or remove it. Also FCD can handle latency and discontinuity problems easily. Such behavior can be expressed by using conditional gate.[1]

On the other side, an SDG model can substitute several FCD models into one integrated model. Because of this integraty, it has been attentioned in model-based methodology.[5] However SDG lacks the macroscopic and global view for the trend of the system. It is because SDG integrates the local and microscopic relations of the variables without modification. This difficiency makes the making of the path of the fault propagation have many problems and many constraints. SDG can not express the faulty state without unmeasured variables. Rightous state variables must be included, whether they are measured variables or not. If not, the fault-expression with SDG is apt to go wrong with real world. But essentional state variables are likely to be excluded and the derivation of the fault propagation pattern is not easy. In contrast to SDG, FCD can drive the propagation patten only with measured variables.

3-2. FCD construction method.

The most difficult thing to constructed a FCD is that there is no structured method for FCD generation. The characteristic that FCD express the thendency of the system according to the kind or state of the variable make the automatic synthesis be more difficult. And the dynamic pattern of the fault propagation, that is, conditional gate which express the path affected by the state of the variables, prevents us from making the FCD automatically. The heuristics that would be included in FCD have same effect. At previous works, SDG is generated first for FCD, then FCD is synthesized by tracing the variables in the SDG, considering the process state. This method is very tedious. To make the SDG and FCD becomes double burdens. Also the generation of SDG become relatively important. For FCD generation, dynamic simulation can be used. FCD generation can be performed by simulating the system dynamically and analyzing the result of the simulation. But this method have some troubles due to the difficulties of dynamic simulation. In addition to the difficulty for the precise modelling for dynamic simulation, if the unit have difficulty in modelling, much more troubles are generated. For getting out of these troubles, the reaserch for development of the qualitative simulation is goning on. Qualitative simulation is similiar to quantitative simulation from the viewpoint that it performs the modelling for the natural phenomena and provide the information which makes real world be interpreted by analyzing the result of the simulation. But qualitative simulation can simulate with the incomplete information and imperfect relations of the variables while quantitative simulation need precise modelling. Qualitative simulation is easy to modelling and relatively speedy, but it have troubles. The generation of the spurious solution which is not the tendency of the real system can not be avoidable. As the system becomes bigger, the number of spurious solution becomes larger. To treat these troubles effectively is a key for sucess of qualitative simulation.

3-3. qualitative simulation and FCD construction case study.

The adaptation of the qualitative simulation laying stress on QSIM algorithm of Kuiper to buffer system is described. Figure 4. is the flow chart of the QSIM algorithm.[7]

The Figure 5. shows simple buffer tank system. The level of the tank controlled by the propotional controller. The controlled variable is outlet flow.

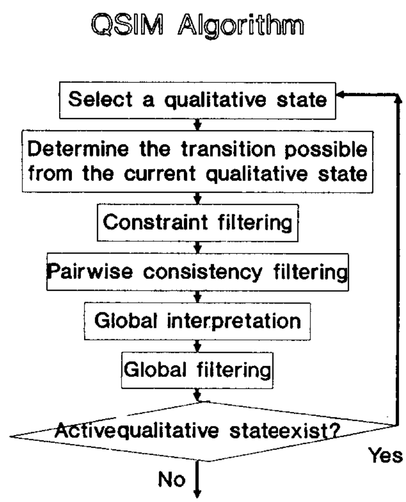

Figure 4. QSIM algorithm chart

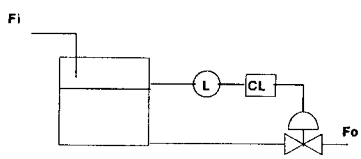

Figure 5. Simple tank buffer system

The model of this process is

tank : A·dL/dt = Fi - Fo

controller : CL = L - LSET

Fo = M-(CL)

where

A : crosssectional area of the tank

L : the level of the tank

Fi : inlet flow of the tank

Fo : outlet flow of the tank

CL : controller output

LSET : set point of the level controller

M- in this model is constraint which means that one variable decrease monotonically as the other variable increase, and vice versa. The constraints in use and their meaning is follows.

A = M+(B) :A monotonically increase as B increase, and vice versa

A = M-(B) :A monotonically decrease as B increase ,and vice versa

A = DERIV(B) :A is derivative of B

A = ADD(B,C) :A = B + C

A = MULT(B,C) :A = B * C

A = MINUS(B) :A = -B

By using these constraints, model can be expressed as following relations

dL/dt = DERIV(L)

Fi = ADD(dL/dt, Fo)

L = ADD(CL, LSET)

Fo = M-(CL)

Each variable has special value called landmark value. For example, tank level L has following values.

0 < Lstd < Lmax < Linf

Corresponding values needed are pairs of values of the each variable in one constraint at same time. For example, controller output CL must be 0 when tank level L is equal to set point LSET.

L = (CL, LSET) (L, CL, LSET) = (Lstd, 0, LSETsp)

The possible tendency and value of each variable is constrained for some time step. The tendency of the variable which is steady state can maintain steady state, or change to decreaseing state or increasing state. But the tendency of the variable which is increasing state cannot change to decreasing state directly without going through steady state when time step go on. And each variable cannot jump over two landmark values. These limitation and the properties of the constraints control the transition of the variable. To limit transition by some rules is called filtering. There are constriant filtering by the properties of the constraints, corresponding value filtering by corresponding values, pairwise filtering by use of the pairs of variables transisted, global filtering which eliminate the cyclic result by the observation of global trend.

FCD can be generated when pipe blockage of the tank buffer system occurs. Figure 6. shows the FCD for this senario.

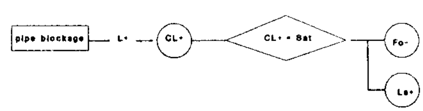

Figure 6. FCD for pipe blockage

The initial values of the variables for qualitative simulation are

dL/dt : < 0, std >

L : <Lstd, std>

Fi : <Fstd, std>

Fo : <Fstd, dec>

LSET : <LSET*, std>

CL : < 0, std >

If the simulation is performed by using these data, two set of the tendency of the variables are found.

	solution 1		solution 2
dL/dt	: std -> inc -> std	dL/dt	: std -> inc -> inc
L	: std -> inc -> std	L	: std -> inc -> inc
Fi	: std -> std -> std	Fi	: std -> std -> std
Fo	: std -> dec -> std	Fo	: std -> dec -> dec
LSET	: std -> std -> std	LSET	: std -> std -> std
CL	: std -> inc -> std	CL	: std -> inc -> inc

One means that the system is recovered by controller, the other means that the tank level becomes higher, because of the saturation of the controller. These results get along with the conditional gate of the FCD.

The defects of qualitative simulation is showed in this case. After the filtering, there are many spurious solutions. These solutions can be removed by adding constraints, ordering of the correspondig values as well as correspondig value set, and directly controlling the transition of the variables considering the faults.

4. Conclusion

The main factors in developing a fault diagnosis system and a safety assessment system of a chemical process are constructing an appropriate knowledge model and building a diagnosis strategy. These two factors are combined in accordance with an accuracy, effectiveness, and usefulness of a diagnosis system itself or building such system. In our previous research, the accuracy of the diagnosis system in real plant application was the main issue in spite of a duality of knowledge models(Symptom tree and Fault Consequence Digraph) and a complexity of the diagnosis strategy.

In this research, existing two knowledge representation models - symptom tree model and the fault-consequence digraph- can be synthesized. The integrated model can be constructed using these synthesizing theory and experience. Also a fault diagnosis system and a safety assessment system can be derived using this new knowledge model.

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