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On-Line Fault Diagnosis Using the Signed Directed Graph

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Fault diagnosis using structural knowledge, namely, the signed directed graph (SDG), is presented. A design procedure is proposed to overcome several problems associated with the SDG: (1) it produces spurious (multiple) interpretations and (2) it may delete the true interpretation when the process variable is going through nonsingle transition (this is frequently encountered in a control loop). The proposed method has the following features: (1) discretize a continuous process response into several states, and different conditions (truth tables) are imposed to check the consistency of fault propagation; (2) find the dominant path of fault propagation using steady-state gains; and (3) express the variable associated with the integrator in the velocity form. The first feature improves the modularity of the diagnostic system, which in turn makes the design and maintenance of the diagnostic system easy. Furthermore, improved diagnostic resolution can be achieved by imposing more stringent conditions at different states and by finding the dominant path. The third feature enables the system to handle variables with nonsingle transition in a control loop. A CSTR example is used to illustrate the design procedure. Simulation results show that the proposed approach based on the SDG provides an attractive alternative for process diagnosis.

1. Introduction

In an operating chemical plant, product quality and plant safety are maintained by controlling process variables. If there are any equipment malfunctions or human error, the product quality may suffer, the plant may be forced to shut down, and catastrophic events such as explosions, fires, or the release of toxic chemicals may occur. In most chemical plants, abnormal measurements trigger alarms in the central control room, which alert process operators. It is normally the operator's responsibility to take remedial actions to restore the plant to normal operation or to initiate the shut-down procedure. Hence, operators must find out the causes of process upsets, i.e., the fault origin. The process of finding the fault origin is called "fault diagnosis".

Conventionally, fault diagnosis is the responsibility of the process operators. It is not an easy task for the operators to diagnose process faults because many factors affect the performance of the operators responding to a process alarm. These factors include the number and frequency of alarm firing, the mode of presentation of data to process operators, the complexity of the plant, and the operator's training, experience, alertness, and reaction to stress. These factors make the fault diagnosis by operators difficult. Therefore, the automated diagnostic system becomes attractive.

Techniques for automated diagnosis can be classified into qualitative approach and quantitative approach depending on how rigorous the model is. Quantitative fault diagnosis utilizes a rigorous process model and on-line measurements to back-calculate unmeasured process variables as well as model parameters (Isermann, 1984). This kind of approach can accurately find out the sources of process upsets and the magnitude of deviation. However, the quantitative approach generally requires extensive engineering manpower and computation horsepower. Furthermore, the number of faults to be diagnosed is limited by the degrees of freedom available. Therefore, the versatility of the quantitative approach is quite limited.

As pointed out by many AI researchers (de Kleer and Brown, 1984), humans appear to use a qualitative causal calculus in reasoning how a physical system behaves.

Therefore, qualitative (process) knowledge should be able to identify the core knowledge underlying physical intuition. In qualitative fault diagnosis, different kinds of knowledge representations result in various diagnosis systems. Typical knowledge representations include (1) shallow knowledge representation and (2) deep knowledge representation (Moore and Kramer, 1986; Fink and Lusth, 1987; Milne, 1987). Shallow knowledge describes the empirical relationships between irregularities in the system behavior and system faults. This kind of diagnostic system is typified by the expert system approach, which includes a knowledge base composed of heuristic rules and a mechanism for firing rules, i.e., inference engine. Generally speaking, heuristics-based systems suffer from lack of completeness and consistency. This is especially true in engineering applications.

In chemical engineering, most process knowledge is well structured and the knowledge can be easily characterized by well-known physical principles. Therefore, the use of deep models in knowledge representation becomes attractive. One common practice is the fault tree analysis (Lees, 1983). A composite of deep and shallow knowledge is employed in the fault tree analysis. Since there exist a lot of control loops and recycle streams in chemical processes, fault tree analysis is not suitable for on-line fault diagnosis during transient. Another qualitative approach to fault diagnosis based on deep process knowledge is the signed directed graph (SDG). The SDG is commonly used to represent the causal effects between process variables (Kramer and Palowitch, 1987; Umeda et al., 1980). O'Shima and co-workers (Iri et al., 1979; Shiozaki et al., 1985) applied SDG to fault diagnosis. The approach of O'Shima is basically algorithmic in nature, which requires extensive computational horsepower. Kramer and Palowitch (1987) pioneered the modern version of the fault diagnostic system based on SDG. The rule-based forward reasoning approach of Kramer and Palowitch (1987) provides an efficient method in identifying the possible cause of process upset. Despite recent advances in the SDG, several fundamental issues about the SDG remain unresolved. One is that qualitative SDG diagnostic systems produce *spurious* interpretations (multiple solutions). By spurious interpretation we mean that the true fault origin is *included* in addition to other interpretations. Another problem is that SDG diagnostic systems may produce *erroneous* interpretation. By erroneous interpretation we mean the true fault origin is *excluded* from the interpre-

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tation. This is especially true when process variables go through nonsingle transition. It is a serious situation if an automated fault diagnostic system excludes the true interpretation from all possible interpretations.

The objective of this work is to overcome problems associated with spurious and erroneous interpretations in the SDG. The development in this paper is based on the fundamental structure of Kramer and Palowitch (1987). This paper is organized as follows. The approach to construct the SDG is presented. In order to reduce the number of spurious interpretation, the procedure for simplifying the SDG is proposed. A more stringent condition is imposed to verify the fault propagation as the system response progresses toward a new steady state. In order to improve the correctness of the diagnosis, transformation is proposed for variables associated with an integrator to match the *signed* constraint imposed by the SDG. A brief discussion on deriving rules from a SDG is presented. Finally, a CSTR example is used to illustrate the effectiveness of the proposed method.

2. SDG for Process Diagnosis

The first step in the qualitative approach is to transform the quantitatively precise process measurements into qualitative states of high, normal, and low. For example, $x \in \mathcal{R}$ is transformed to $x \in \{+, 0, -\}$. Then, the causal relationships between variables, characterized by the sign (+ or -), can be constructed from the system topology.

$$A \xrightarrow{+ \text{ or } -} B$$

In the SDG, the nodes (A and B) correspond to the process variables and the branch represents the immediate influence between the nodes. Positive or negative influence, i.e., promotion or suppression, is distinguished by the sign, "+" or "-", assigned to the branch. The SDG illustrates the influence of the deviation of the initial node from its normal operating value on the deviation of the terminal node from its normal operating value. Process variables consequently need to be converted to deviation variables (Luyben, 1973, p 180) before the SDG is constructed. The advantage of describing physical systems by the SDG is that we can visualize how the system behaves.

2.1. Constructing the SDG. The SDG for chemical processes can be built from (Iri et al., 1979) (1) plant operation data and/or experienced operator and (2) a mathematical model of the process or process simulator. When the operation data and the experiences of operators are not sufficient to obtain a consistent representation of the process, it is desirable to construct the SDG from a process model. The process model usually consists of ODE's and algebraic equations.

In general, an ODE can be written in the form

$$dx_i/dt = f_i(x_1, x_2, \dots, x_n) \quad (1)$$

A branch is defined to start from x_j and end at x_i if $(\partial f_i / \partial x_j) \neq 0$. The sign of $\partial f_i / \partial x_j$ is assigned to the branch. For a linear algebraic equation of the form

$$x_i = \sum_{j=1}^n a_{ij} x_j \quad (2)$$

a branch is defined to start from x_j and end at x_i . The sign of a_{ij} is assigned to the branch. The SDG constructed by this principle is capable of describing most physical systems qualitatively.

2.2. Forward Simulation Using the SDG. The process of finding a fault origin from process measurement is basically a *backward* reasoning process. The reasoning of most process experts is, however, a *forward* reasoning. This paper adopts the concept of forward simulation

Table I. Dynamic Truth Table

A	B		
	+	0	-
$A \xrightarrow{+} B$			
+	T	T	F
0	F	T	F
-	F	T	T
$A \xrightarrow{-} B$			
+	F	T	T
0	F	T	F
-	T	T	F

Table II. Steady-State Truth Table

A	B		
	+	0	-
$A \xrightarrow{+} B$			
+	T	F	F
0	F	F	F
-	F	F	T
$A \xrightarrow{-} B$			
+	F	F	T
0	F	F	F
-	T	F	F

(reasoning) for fault diagnosis.

The SDG represents the causal pathways of fault propagation. The qualitative state of the terminal node depends on the sign of the branch as well as the state of the initial node. A branch is said to be *consistent* if the initial node, A , and the terminal node, B , match the sign on the branch according to the truth table (Table I or II). Fault propagates along consistent branches (Iri et al., 1979). Hence, only consistent branches are considered in process diagnosis.

Truth tables are constructed according to the states of the system response. The letter T (.TRUE.) in the truth table corresponds to a consistent branch according to the measurement pattern of the initial and terminal nodes. For a system under transient, the branch can be termed "consistent" if the initial node deviates from the normal operating point and the terminal node remains unchanged (Table I). This is the result of time delay or time lag in a dynamic system. At steady state, however, a more stringent condition is imposed in the truth table (Table II). As shown in the steady-state truth table (Table II), the consequence of time delay can no longer be tolerated at steady state. Furthermore, since all compensatory variables are removed from the SDG at steady state, i.e., for a given fault origin, all of the remaining variables in the steady-state SDG should have either positive or negative deviation, a normal A ($A = 0$) and B ($B = 0$) implies fault does not propagate through the branch. Therefore, for the purpose of fault diagnosis, $A = 0$ and $B = 0$ is termed F (.FALSE.) at steady state. Changing the truth table according to the states is an effective tool in improving diagnostic resolution.

Similar to the approach of Kramer and Palowitch (1987), single fault assumption is made in this work. Hence, the SDG of the overall system can be reduced to an individual subgraph composed of only one root node. An identified fault origin is the root node of a subgraph with all branches being consistent. Fault diagnosis is to trace all the possible fault origins given on-line measurements.

3. Simplifying the SDG

The reasons to simplify SDG are (1) practical need and (2) promoting diagnostic resolution. The latter, diagnostic

Figure 1. Simplifying SDG according to measured/unmeasured variables: (A) the original SDG, (B) lumping sensors with the variables, (C) removing the unmeasured variable, and (C') the SDG for sensor failure in the control loop.

resolution (spurious solution), is the drawback of most qualitative diagnostic systems. Simplifying the SDG reduces the number of branches which, in term, eliminates some spurious interpretations. Furthermore, different conditions, e.g., truth tables in Tables I and II, can be imposed on the simplified SDG, which becomes very effective in reducing further the number of spurious interpretations. The SDG is simplified according to (1) measured/unmeasured variables, (2) state of the system, and (3) additional process knowledge, namely, the dominant effect. In the first step, information about the process configuration is necessary. In the second step, the values of on-line process measurements are necessary. In the third step, an expert's judgement or process model is required.

3.1. Simplifying SDG According to Measured/Unmeasured Variables. If the measurement is rapid, any working sensor can be lumped with its corresponding variable node without generating spurious or erroneous interpretation except for the measurement of the controlled variable. Generally, the sensor of a controlled variable cannot be lumped with its corresponding variable if the sensor is a potential root node (Palowitch and Kramer, 1986). Disregarding this fact may lead to erroneous interpretation when the fault is developed in the sensor of a controlled variable. In a SDG, there might be some unmeasured nodes. These nodes are useless in fault diagnosis since there is not any measurement available to match with. Therefore, unmeasured nodes are removed. Branches through unmeasured nodes are replaced by a single branch connecting measured nodes, with the sign on the new branch being the product of the signs of the branches it replaces. However, unmeasured variables cannot be removed if it is a potential root node. It should be noticed that the removal of unmeasured nodes removes signed constraints from a SDG and in some occasions the simplified SDG is not equivalent to the original SDG. As pointed out by Kramer and Palowitch (1987, Figure 11), when there are multiple pathways from the root node to the unmeasured node, the removal of that unmeasured node may lead to a spurious pathway. In other occasions, removal of unmeasured nodes may simply delete feedback information from the SDG.

The SDG in Figure 1 illustrates how the sensor nodes or unmeasured nodes are lumped with the original variables as shown in Figure 1A; nodes A, B, C, and D are process variables, E is the controlled variable, and F is the manipulated variable. The sensor nodes C_m , D_m , E_m , and F_m are lumped with the original variables as shown in

Figure 2. Original SDG for the fault origin $F_{j,max}$.

Figure 3. Lumped SDG for the fault origin $F_{j,max}$.

Figure 1B. If unmeasured node B is removed, a new branch between A and C is formed and the sign on the new branch is the product of signs for branches A-B and B-C (Figure 1C). If the sensor node for controlled variable E, E_m , is a potential root node, the sub-SDG for sensor (E_m) failure is shown in Figure 1C'. The SDG in Figure 2 represents the causal effects in a CSTR when the maximum cooling water flow rate, $F_{j,max}$, is the fault origin. The SDG in Figure 2 is simplified by removing unmeasured nodes VT, K, and CA (Figure 3). Notice that the removal of K and CA in Figure 2 deletes the information about feedback effects on T. The loss of feedback information may not lead to erroneous interpretation under the current approach; it may result in a different interpretation for future generation of the SDG diagnosis system (e.g., system capable of handling nonsingle transition in a direct manner).

3.2. Simplifying SDG According to the States of the System. Kramer and co-workers (Kramer and Palowitch, 1987; Oyeleye and Kramer, 1988) proposed conditional branches and extended SDG (ESDG) to overcome the problems associated with compensatory and/or inverse responses. Regulatory response leads to inconsistency in the branches during transient. A conditional or additional branch is drawn in the same SDG. Despite being able to describe compensatory behavior, their approach lacks modularity.

When a system is disturbed by an asymptotically constant disturbance, it will move toward a new steady state by going through several states. In other words, a continuous process response can be depicted by some discrete

Figure 4. Simplified SDG's for the fault origin $F_{j,\max}$ for states (A) $T = 0$, (B) $T_j = 0$, and (C) $F_j = 0$.

states. One advantage of using states to depict the transition of a system response is the diagnostic system becomes very modular. It also satisfies the no function in structure principle emphasized by qualitative physics (de Kleer and Brown, 1984). Hence, it makes the knowledge more structural and promotes the ability to deal with complicated systems. Another advantage from the recognition of states is that different limitations can be imposed on different states, e.g., changing the truth table (which turns out to be very effective to improve diagnostic resolution).

Due to the self-regulating property of the process or the compensating behavior of the control loop, some process variables might return to the original steady states in the face of an asymptotically constant fault. Therefore, the states of a system can be identified depending on whether the compensatory variables return to their original steady state. In a SDG, when a variable returns to the original steady state, its corresponding node will disappear and a new SDG can be constructed accordingly. If the method of state transition is adopted, a number of subgraphs (or the corresponding states) can be used to describe the process response in the face of the same fault origin. The original SDG can be properly reduced (the number of branches and nodes can be properly reduced) according to on-line measurements to improve the resolution in fault diagnosis.

Several approaches can be taken to identify the variables with compensatory behavior. One is purely heuristic, e.g., from experience (the control loop and tank level). Oyeleye and Kramer (1988) identify variables with the compensatory property from system topology. Only necessary conditions are proposed, since the sufficient condition is numerical. In this work, states are obtained from the process model. It should be noticed that the system will not arrive at a new steady state if the fault origin is in the control loops.

An example is presented to illustrate the concept of states. From the steady-state model of the process, the variables F_j , T_j , and T will return to their original steady state given the fault origin, $F_{j,\max}$ (Figure 3). Without detailed dynamic information, each variable can return to its original steady state before the other. Therefore, three states, A (for $T = 0$), B (for $T_j = 0$), and C (for $F_j = 0$), can be constructed accordingly (Figure 4). Some other states, D, E, and F, can also be identified from the combination of any two variables returning to their steady states (Figure 5). The subgraphs can be simplified as the nodes disappear (Figures 3–5). Finally, the ultimate steady state is reached when all variables with compensatory behavior return to their original values (Figure 6). The SDG becomes a tree structure. As shown in Figures 3–6, the number of branches is reduced as the SDG is simplified further. Moreover, the steady-state truth table (Table II)

Figure 5. Simplified SDG's for the fault origin $F_{j,\max}$ for states (D) $T = 0$ and $T_j = 0$, (E) $F_j = 0$ and $T_j = 0$, and (F) $F_j = 0$ and $T = 0$.

Figure 6. Simplified SDG for the fault origin $F_{j,\max}$ at the final steady state: (G) $T = F_j = T_j = 0$.

is used to check the fault propagation in state G. Therefore, better resolution can be achieved with the reduced graph. In this simplification step, modularity is achieved at the expense of memory size of the diagnostic system. This is especially true when the process contains a lot of compensatory variables. However, with additional knowledge of the process dynamics, the number of states can be reduced significantly, since, generally, compensatory variables approach steady state with a certain pattern, e.g., the three compensatory variables approach steady state almost at the same time.

It should be noticed that not all subgraphs can be reduced to a tree structure without further process knowledge. The additional process knowledge is, namely, the dominant effect on each node from all acyclic pathways from the fault origin.

3.3. Simplifying SDG via Additional Process Knowledge. Fault diagnosis using the SDG is often associated with spurious solutions. One reason comes from the multiple pathways of fault propagation. To solve the problem, one must find the dominant effect in the fault propagation. Using experience or process simulation to identify the dominant effect is proposed by Kramer and Palowitch (1987). However, this approach is time-consuming. This paper presents another method, i.e., from steady-state gains, to deal with the problem.

Another example, the preexponential factor (k_0) of the rate constant in a CSTR as the fault origin, is used to illustrate the problem of multiple pathways (Figure 7). In this example, k_0 influences T in two opposite pathways, one is the positive influence and the other is the negative influence. The double propagation pathways are also shown in Figure 7. The SDG in Figure 7 is simplified to A and then to B of Figure 8 from the principle mentioned

Figure 7. Original SDG for the fault origin k_0 .

Figure 8. Simplified SDG's for the fault origin k_0 : (A) the lumped SDG and (B) the lumped SDG with $T = 0$.

Figure 9. SDG for the fault origin k_0 at the final steady state.

earlier. However, the SDG in Figure 8B still consists of double-propagation pathways.

From steady-state analysis, the ultimate response for the fault origin, k_0 , is shown in Figure 9. The ultimate SDG is a tree that is obtained by considering both the sign and numerical values in the equations. From the results of the steady-state analysis (Figure 9), the dominant pathway can be determined. In the example studied (Figure 8A), the dominant pathway from k_0 to T can be determined by using Figure 9. The branch from T to TC is signed negative (-) (Figure 8A) and the branch from k_0 to TC is signed negative (-) as shown in Figure 9. Therefore, the

Figure 10. Simplified SDG's for the fault origin k_0 provided with the dominant effects: (A) $k_0 \rightarrow T$ dominates and (B) $k_0 \rightarrow T$ and $k_0 \rightarrow T_j$ dominate.

Figure 11. (A) SDG for a control loop and (B) system response for an asymptotically constant change in L .

branch from k_0 to T should be signed positive (+) (Figure 10A). The dominant pathway from k_0 to T_j can be determined similarly. In Figure 10A, k_0 influences T_j via T and $T-TC-F_{jc}-F_j$ with opposite sign. However, Figure 9 indicates that k_0 has a negative influence on F_j . Therefore, the pathway $k_0-T-TC-F_{jc}-F_j$ dominates the other. Thus, Figure 10A is simplified to Figure 10B.

By using the above procedure, subgraphs for the fault origin (k_0) can be reduced to simpler graphs or to a tree. Such subgraphs consist of the same number of nodes and less branches. The number of possible patterns that match the reduced subgraph is much less. This implies a better resolution in fault diagnosis.

4. SDG for Control Loops

As pointed out earlier, correct diagnosis can be guaranteed only when all variables going through single transition. By single transition we mean the deviation of the process variable from its initial steady state does not change the sign during transient. When a process variable is going through nonsingle transition, e.g., the underdamped response of the controlled variable, the sign on the branch should be changed to maintain the consistency. In the chemical process, this phenomenon is not very common except for the controlled variables. As with the results of feedback and the integral action in the feedback path, the controlled variables frequently go through nonsingle transition. The sign of a branch changed with process dynamics has a serious impact on the diagnostic systems. The true fault origin can be eliminated during transient. It is common for the qualitative SDG to produce spurious solutions. However, a diagnostic system missing the true fault origin can lead to serious hazard.

A method is proposed to overcome the nonsingle-transition problem associated with the controlled variable. Consider the control loop in Figure 11A where x is the controlled variable, C is the controller output, and M is the manipulated variable. All variables are represented in the form of deviation variables. For the branch $x \rightarrow C$, consider three types of controllers:

- (1) C is the output of a P-only controller

$$C = K_c x, \quad K_c < 0 \quad (3)$$

In this case, the sign of the branch stays the same in all cases.

- (2) C is the output of a I-only controller

$$C = K_c \int x \, dt, \quad K_c < 0 \quad (4)$$

In this case, C stays negative as x goes from positive to negative (Figure 11B). Thus, the sign of the branch changes during transient.

- (3) C is the output of a PI controller

$$C = K_c \left[x + \frac{1}{\tau_i} \int x \, dt \right], \quad K_c < 0 \text{ and } \tau_i > 0 \quad (5)$$

In this case, the result is the combination of case 1 and 2. The sign of the branch depends on the dominant term between the proportional and integral actions.

The reason why the SDG fails to deal with the control loop with integral action is obvious. As the name implies, the signed directed graph can deal with signed constraints appropriately instead of the integration. To overcome this problem, a simple approach based on variable transformation is proposed. Equation 4 can be expressed in the discrete form

$$C_k = K_c \sum_{i=1}^k x_i \Delta t \\ = K_c (x_k + x_{k-1} + \dots + x_1) \Delta t \quad (6)$$

and

$$C_{k-1} = K_c (x_{k-1} + \dots + x_1) \Delta t \quad (7)$$

Subtracting eq 7 from eq 6 gives

$$\Delta C_k = C_k - C_{k-1} = K_c x_k \Delta t \quad (8)$$

Equation 8 shows that when C is expressed in the velocity form, ΔC , a simple signed relationship exists between ΔC and x . Therefore, the changing sign problem associated with integral action can be eliminated by transforming the terminal node (C) into the velocity form (ΔC). Notice that when a PI controller is used, we do not know which effect (P or I) is dominant. Therefore, the velocity form, ΔC , should be checked in addition to the standard form, C .

In a diagnostic system, the relationship between controller output (C) and the controlled variable (x) can be described in terms of logical operators, e.g., p describing a positive branch and m describing a negative branch. For P-only, I-only, and PI controllers, the expressions are as follows: (1) P-only controller, $(m \times C)$; (2) I-only controller, $(m \times \Delta C)$; (3) PI controller, $(m \times C) \text{ or } (m \times \Delta C)$. If the result from the logical calculation is true, then the branch is consistent. The method proposed here can avoid generating erroneous interpretation when the controlled variable goes through nonsingle transition.

Under signed constraint, variable transformation can be taken to deal with unusual dynamics between nodes such that the causal effect between the transformed variable can be described by signs. In a control loop, a simple transformation, the velocity form, of the controlled variable

makes the branch, $x \rightarrow \Delta C$, be appropriately described by a sign. Notice that the node variable C (instead of the velocity form ΔC) is used for the next branch, e.g., $C \rightarrow M$ in Figure 11.

5. Implementing SDG for On-Line Diagnosis

From the on-going discussion, SDG is constructed for a single fault origin followed by simplifying into the simpler SDG according to states of the system response. The next step is to transform the SDG's into an executable form for on-line diagnosis. It is important to have a diagnostic system that is computationally efficient and yet is effective in diagnosing system failures. More importantly, it has to be modular since a SDG diagnostic system can become extremely complicated as the process becomes larger.

5.1. Expression for the Variables. In a SDG, every node variable is expressed in terms of deviation index, which is the deviation variable normalized by some threshold (Palowitch and Kramer, 1986). The deviation index is

$$x = \frac{\text{measured } x - \text{normal operating value of } x}{\text{threshold of } x}$$

The quantitative precise variable, x , is transformed into a qualitative variable. It takes the value of +, 0, or - for $x \geq 1$, $1 > x > -1$, or $-1 \geq x$, respectively.

5.2. Deriving Rules from a Single SDG. Kramer and Palowitch (1987) proposed the rule-based approach for the SDG. The rule-based, forward reasoning system is easy to program and computationally efficient. Therefore, the rule-based approach is adopted in this work. The final diagnostic system consists of sets of rules that are assembled by logical functions, e.g., p and m , describing the consistency of all branches in a SDG. The logical functions used in this work are classified according to states:

- (1) during transient

$$p_d AB \Leftrightarrow A \xrightarrow{+} B$$

$$m_d AB \Leftrightarrow A \xrightarrow{-} B$$

- (2) at steady state

$$p_s AB \Leftrightarrow A \xrightarrow{+} B$$

$$m_s AB \Leftrightarrow A \xrightarrow{-} B$$

The truth value, e.g., T or F, of a logical operation depends on the signs of the initial and terminal nodes as well as the corresponding truth table (Table I or II). Table I is used for p_d and m_d and Table II is employed for p_s and m_s .

For branches merging into a single node n_i , the premise can be written as (Kramer and Palowitch, 1987)

$$[(\ast k_1 n_i) \text{ OR } (\ast k_2 n_i) \text{ OR } \dots \text{ OR } (\ast k_j n_i)]$$

where $k_1, k_2, \dots, k_j$ are the immediate input nodes to n_i and $\ast$ is a corresponding logical function, which can be p_d, m_d, p_s , or m_s . This procedure is repeated for every node to establish part of the premise. The premise for each node is connected via the .AND. operator.

[premise for node 1].AND.[premise for node 2].AND. ...

Since the root node normally is not measurable, the expression for the immediate node right after the root node needs to be modified. For example, for the branch $A \xrightarrow{+} B$ with a fault rooted at A with a positive deviation, the

Figure 12. CSTR example.

expression for node *B* is

(1) during transient

$$[B.GE.0]$$

(2) at steady state

$$[B.GT.0]$$

The operators .GE. and .GT. stand for greater than or equal to and greater than, respectively.

Therefore, a pair of rules can be constructed for a single graph with positive and negative deviations in the root node. For example, the rule for state *D* in Figure 5 with a positive deviation in $F_{j,max}$ can be expressed as

$$\text{IF } \{[F_{j,max}.GE.0].\text{AND}.[p_d F_j TC].\text{AND}.[p_d TCF_{jc}]\}$$

$$\text{THEN } F_{j,max} = +$$

Notice that the qualitative values of T_j , T , and rest of the measurements (not shown in this subgraph) are checked to be zero before firing this rule. The rule for a negative deviation in $F_{j,max}$ is similar except that $[F_{j,max}.LE.0]$ is used in the premise instead of $[F_{j,max}.GE.0]$. Once steady state is reached (in this paper steady state is verified by checking whether the incremental changes of *all* process variables are less than some thresholds), the rule to diagnose $F_{j,max}$ is (state *G* is Figure 6)

$$\text{IF } \{[TC.GT.0].\text{AND}.[p_s TCF_{jc}]\}$$

$$\text{THEN } F_{j,max} = +$$

If the truth value of the premise is .TRUE., then $F_{j,max}$ is the fault origin with a positive deviation from its nominal value.

5.3. Combining Sets of Rules for a Fault Origin.

Since the complete response of an asymptotically constant fault is discretized into several states, rules describing different states for a given fault origin with certain fault direction (e.g., positive deviation) are combined together as a set of rules. For a given measurement pattern, the state is classified first and then the rule describing that particular state (in any given set of rules) is fired. Notice that the firing of the rule describing steady-state behavior requires checking incremental changes of *all* process measurements as mentioned earlier. Furthermore, all possible faults (all possible sets) are checked at each execution.

In summary, a systematic procedure to construct a process diagnostic system is proposed. By classifying process response into states, the diagnostic system becomes quite modular, which is easy to construct and maintain. However, the modularity is achieved at the expense of the size (the memory capacity in a computer) of the diagnostic system. Certainly, the size of the system can be reduced

Table III. Measurements for On-Line Diagnosis

symbol	measurements or control signal
T_0	reactor feed temp
T	reactor temp
T_j	cooling water outlet temp
F_j	cooling water flow rate
TS	temp controller setpoint
TC	temp controller output
F_{jC}	cooling water flow controller output
V	reactor level
VS	reactor level controller setpoint
VC	reactor level controller output

Figure 13. SDG for the CSTR example.

with appropriate dynamic information (by deleting states that do not occur in practice). More importantly, we believe that the ease of construction and maintenance is more important for the successful application of a diagnostic system than some hardware requirement.

6. Application

6.1. Process Diagnosed. A CSTR example is used to test the effectiveness of the proposed diagnostic system. The process is a CSTR undergoing an irreversible first-order exothermic reaction (Figure 12). Parameter values are taken from the literature (Luyben, 1973, p 144). The reactor temperature (T) is controlled by manipulating the cooling water flow rate (F_j). A temperature/flow cascade controller is used, assuming perfect flow control. The reactor level (V) is controlled by changing the outlet flow rate (F). PI controllers are used to maintain corresponding setpoints. Tuning constants are $K_c = 32$ and $\tau_i = 0.9$ (1/h) for the temperature loop and $K_c = 10$ and $\tau_i = 0.6$ (1/h) for the level loop, respectively. Ten measurements and control signals are available for on-line fault diagnosis as shown in Table III.

6.2. Diagnostic System. In order to construct the SDG, equations describing the CSTR (Luyben, 1973, p 144) are linearized. The SDG is constructed according to the procedure in section 2. Figure 13 shows the SDG for the CSTR example. Notice the SDG constructed is rather *robust* since changes in the parameters generally will not affect the graph *unless* the coefficients in the linearized equation change sign. The subgraph for each root node (fault origin) can be derived from Figure 13. Figures 2 and 7 show the SDG's for the fault origin $F_{j,max}$ and k_0 , respectively. An individual SDG is simplified according to the availability of measurements, the number of compensatory variables, and the dominant effects. Figures 2-6 and 7-10 illustrate the simplification procedure for the root nodes $F_{j,max}$ and k_0 . Fifteen fault origins are considered in this diagnostic system, which include external disturbances, degradation in the performance of equipments, malfunctions in the instrumentations, and equipment

Table IV. Fault Origins

symbol	fault origin
F_0	changes in the feed flow rate
CA_0	changes in the feed concn
T_0	changes in the feed temp
T_{j0}	changes in the cooling water inlet temp
k_0	changes in the preexponential factor of rate constant
U	changes in the overall heat-transfer coeff
VS	bias in the level controller setpoint
TS	bias in the temp controller setpoint
VC	malfunction in the level controller
TC	malfunction in the temp controller
F_jC	malfunction in cooling water flow controller
VL	failure in the control valve in the level loop
VT	failure in the control valve in the temp loop
$F_{j,max}$	blockage in the reactor outlet line
$F_{j,max}$	blockage in the cooling water line

failures. Table IV gives all of the fault origins considered. Chang (1988) gave a complete list of digraphs for all fault origins. The outputs of temperature and flow controller are expressed in velocity form in addition to the standard representations, since PI controllers are used throughout. Thirty sets of rules are constructed for all 15 fault origins. The rules are programmed in FORTRAN and require only logical expressions and simple calculations (for the deviation indexes).

6.3. Results. Two diagnostic systems, conventional and proposed systems, are used to test the effectiveness of the proposed method. The only differences between these two systems are (1) the proposed method uses both the transient response and steady-state truth tables (Tables I and II) to check the consistency in a SDG as oppose to the single truth table (Table I) approach in the conventional method and (2) the controller outputs in the proposed approach are expressed in the velocity form in addition to the deviation index expression, which is the only expression employed in the conventional approach. The diagnostic system samples on-line measurements every 3 min and makes possible fault interpretations. The thresholds used in this work are 0.2% in the control signals and 0.3 °F in the temperatures. For a fault developed in $F_{j,max}$ (a 20% step decrease in $F_{j,max}$), the proposed method is quite effective in reducing the number of *spurious* interpretations as shown in Figure 14. In Figure 14, all possible fault origins with positive and negative deviations are listed and the true fault origin is indicated by "F" along the ordinate. In this case, this is a decrease in $F_{j,max}$. The + (-) sign (Figure 14) indicates that the diagnostic system interprets a + (-) deviation in that particular root variable with respect to time. Initially, almost 10 faults are diagnosed according to the measurement pattern as shown in Figure 14. An abrupt change in the diagnostic results can be seen at 1 h after the fault developed. The reason is steady state is verified by the diagnostic system, and rules based on the final steady-state digraphs are fired. Notice that all of the compensatory variables reach steady state almost at the same time in this case. As shown in Figure 14, the proposed method does not yield spurious solution after that point. Therefore, the improvement in the diagnostic resolution comes from the fact that a more stringent condition, i.e., the steady-state truth table, is imposed. The noisy interpretations (e.g., the + or - interpretations at $t = 2.5$ h) are the consequences of the sizes of thresholds selected. This situation can be improved a little by modifying the thresholds. Furthermore, the coexistence of both the + and - deviations for the same node variable is the consequence of allowing time delay and time lag in the truth table of transient response (Table I). Figure 14 typifies the comparison for most fault origins

Figure 14. Diagnosed results for a fault in $F_{j,max}$: (A, top) conventional method and (B, bottom) proposed method.

investigated. Figure 15 shows that the proposed method gives *correct* interpretation when a biased setpoint is developed in the level controller (VS). In contrast, the conventional approach fails to diagnose the fault for a long period of time ($t = 1.25$ – 2.5 h; Figure 15A). The improvement in the correctness comes from the velocity form representation for the controller output. As the fault developed (a biased setpoint, VS), the reactor temperature goes through a nonsingle transition at 1.25 h after the fault

Figure 15. Diagnosed results for a fault in the setpoint of the level controller (VS): (A, top) conventional method and (B, bottom) proposed method.

developed as shown in Figure 16. The conventional diagnostic system fails to produce correct diagnosis from that point and restores correct diagnosis after the temperature returns to a nominal value (within the threshold). The results show that the proposed method is effective in eliminating spurious interpretations and can produce a correct diagnosis when the controlled variables go through nonsingle transition. Change (1988) gives simulation re-

Figure 16. Responses of reactor temperature (T) and temperature controller output (TC) when a fault is developed in the setpoint of the level controller.

sults for all 15 fault origins.

7. Conclusion

A systematic design procedure is proposed for constructing the rule-based fault diagnostic system using the SDG. The proposed approach offers a partial solution to some known problems associated with the SDG: (1) it produces spurious (multiple) interpretations as a consequence of the qualitative nature of the SDG and (2) it may produce an erroneous (incorrect) interpretation when the node variables go through nonsingle transition.

First, a complete process response is discretized into some discrete states according to the compensatory nature of the system. The SDG is simplified according to the states. Since a subgraph cannot be simplified to a tree structure at steady state, additional process knowledge is needed. The steady-state gains are used to simplify the subgraph into a tree structure. Furthermore, different conditions, i.e., different truth tables, are imposed on different states to check the consistency in the branches. This turns out to be very effective in eliminating spurious interpretations. For the second problem, variable transformation is proposed for the controller output. The unusual dynamics, e.g., the integration, can be appropriately described by the signed constraint with the transformed variable that is capable of handling the nonsingle-transition problem in the controlled variable. Since the SDG is simplified according to states, as opposed to branches being added to the SDG, e.g., ESDG or conditional branch approach (Kramer and Palowitch, 1987; Oyeleye and Kramer, 1988), the modular nature of the proposed method makes the diagnostic system easy to design and maintain. A CSTR example is used to illustrate the effectiveness of the proposed method. Simulation results show that the pro-

posed method gives significant improvement over the conventional approach in reducing spurious or erroneous interpretations.

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Nomenclature

C = controller output
 CA = concentration of reactant A
 CA_0 = feed concentration of reactant A
 F = .FALSE.
 F = reactor outlet flow rate
 F_0 = reactor inlet flow rate
 F_j = cooling water flow rate in the jacket
 F_C = cooling water flow controller output
 F_{jm} = measured cooling water flow rate in the jacket
 $F_{j,max}$ = maximum cooling water flow rate
 F_{max} = maximum reactor outlet flow rate
 k = rate constant
 k_0 = preexponential factor of the rate constant
 K_c = controller gain
 m = logical function for negative branches
 M = manipulated variable
 p = logical function for positive branches
 T = .TRUE.
 T = reactor temperature
 T_0 = reactor inlet temperature
 T_{0m} = measured reactor inlet temperature
 TC = temperature controller output
 T_j = cooling water outlet temperature
 T_{j0} = cooling water inlet temperature
 T'_{jm} = measured cooling water outlet temperature
 TS = temperature controller setpoint
 U = overall heat-transfer coefficient
 V = reactor level
 VC = reactor level controller output
 VL = control valve in the level loop
 VS = reactor level set point
 VT = control valve in the temperature loop
 x = controlled variable

Greek Symbols

ΔC = velocity form for C ($\Delta C = C_k - C_{k-1}$)

τ_i = reset time

Subscripts

d = states during transient

m = measured variable

s = steady state

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