Systematic Development of Automata Generated Languages for Fault Diagnosis in Continuous Chemical Processes

Chuei-Tin Chang. Jung-Yang Chen

National Cheng Kung University, Tainan, Taiwan 70101,
ROC (Tel:886-6-275-7575 ext. 62663; e-mail: ctchang@mail.ncku.edu.tw).

Abstract: A SDG-based simulation procedure is presented in this study to qualitatively predict all possible effects of one or more fault propagating in a given process system. All possible state evolution behaviors are characterized with an automaton model. By selecting a set of on-line sensors, the corresponding diagnoser can be constructed and the diagnosability of every fault origin can be determined accordingly. Furthermore, it is also possible to construct a formal diagnostic language on the basis of this diagnoser. Every string (word) in the language is then encoded into an IF-THEN rule and, consequently, a comprehensive fuzzy inference system can be synthesized for on-line diagnosis. The feasibility of this approach is demonstrated with a simple example in this paper.

Keywords: fault diagnosis, automata, signed directed graph, formal language, fuzzy logic.

1. INTRODUCTION

The fault diagnosis methods have been widely recognized as indispensable tools for enhancing process safety. Generally speaking, they could be classified into three distinct groups, i.e., the model based approaches, the knowledge based approaches, and the data-analysis based approaches (Venkatasubramanian et al., 2003a, b). However, in order to carry out these strategies on-line, it is usually necessary to first analyze the historical data and/or operational experiences obtained during *every* serious accident. This requirement cannot always be satisfied in practice.

To circumvent the above drawbacks, a qualitative cause-and-effect model, i.e., the signed directed graph (SDG), is used in the present study to characterize fault propagation mechanisms. The advantage of this modelling approach is mainly due to the fact that the causal relations in process systems can always be established according to generic engineering principles without any quantitative knowledge. On the other hand, it should be noted that such causal models are basically static in nature. Many SDG-based fault identification techniques were therefore implemented on the basis of the *steady-state* symptoms only, e.g., Maurya et al. (2006). Since the effects of fault(s) and/or failure(s) usually propagate throughout the entire system dynamically in sequence, a series of intermediate events may occur before the inception of catastrophic consequences. Thus, the performance of a qualitative diagnosis scheme should be evaluated not only in terms of its correctness but also its timeliness.

To enhance diagnostic efficiency, it is obviously necessary to consider the precedence order (in time) of various fault propagation effects derived from the qualitative models. Extensive studies have already been carried out to develop effective diagnosis strategies by incorporating both the eventual symptoms and also their *occurrence order* into a fuzzy inference system (FIS). This approach has been applied successfully to a number of loop-free processes (Chang et al., 2002) and also to systems with feedback and/or feed forward control loops (Chang and Chang, 2003; Chen and Chang, 2006; 2007).

Despite the fact that diagnostic performance can be significantly improved with the aforementioned technique, the representation, analysis and synthesis of inference systems are still very cumbersome. In particular, many different versions of the symptom occurrence orders can often be deduced from a single fault origin on the basis of SDG model. Manual enumeration of all such scenarios for all origins may become intractable even for a moderately complex system. Furthermore, the diagnosability issues concerning the resulting FIS have never been systematically addressed in the past. Thus, there is a definite need to develop a unified theoretical framework to extract the intrinsic features of dynamic fault propagation mechanisms. Our concern here is primarily with the sequence of system states visited after the occurrence of fault origin(s) and also the associated events causing the state transitions. A systematic procedure is proposed in this paper to construct automata and language models for the purpose of representing these sequences accurately and succinctly. As a result, additional insights can be revealed and, also, more compact inference rules can be produced accordingly. A simple example is provided at the end of this paper to demonstrate the feasibility and effectiveness of the proposed procedures for FIS synthesis and for fault diagnosis.

2. AUTOMATA CONSTRUCTON

2.1 Qualitative Simulation Procedure

Although other qualitative models may be equally acceptable, the SDG is adopted in the present study to simulate (or predict) the effects of faults and failures. This is due to the fact that the needed implementation procedure is conceptually straightforward. Notice first that the fault origins can usually be associated with the primal nodes, i.e., the nodes without inputs. A set of five values, i.e., {-10, -1, 0, +1, +10}, may be assigned to every node in the digraph to represent deviation from the normal value of corresponding variable. The value 0 represents the normal steady state. The negative values are used to denote the lower-than-normal states and the positive values signify the opposite. The magnitudes of non-zero deviations, i.e., 1 or 10, can be interpreted qualitatively as "small" and "large" respectively. The causal relation between two variables can be characterized with a directed arc and the corresponding gain. Each gain may also assume one of the five qualitative values mentioned above. The output value of every arc in digraph can be computed with the gain and its input value according to the following equation:

$$v_{out} = \begin{cases} g \times v_{in} & \text{if } -10 \le g \times v_{in} \le +10 \\ +10 & \text{if } g \times v_{in} > +10 \\ -10 & \text{if } g \times v_{in} < -10 \end{cases} \quad (1)$$

where g, v_{in} and v_{out} denote respectively the gain, input and output values. It is obvious that the deviation values of all variables affected by one or more fault origin can always be computed with this formula, but the time at which each deviation occurs is indeterminable. Without the reference of time in the SDG-based simulation results, it can nonetheless be safely assumed that *the change in an input variable should always occur earlier than those in its outputs*. In essence, this is the most basic assumption adopted in this study. Notice that, if the precedence order of various fault propagation effects is to be considered in fault diagnosis, a large number of different versions of qualitative simulation results may be generated accordingly. All such scenarios can be captured with the automaton model described in the sequel.

2.2 System Automata

A formal definition of a deterministic automaton $\mathcal{A}$ can be found in Cassandras and Lafortune (1999). Specifically, it is a six-tuple

$$\mathcal{A} = \left(\mathbb{X}, \mathbb{E}, f, \Gamma, x_0, \mathbb{X}_m\right) \quad (2)$$

where, $\mathbb{X}$ is the set of system states; $\mathbb{E}$ is the finite set of events associated with the transitions in automaton; $f: \mathbb{X} \times \mathbb{E} \rightarrow \mathbb{X}$ is the transition function; $\Gamma: \mathbb{X} \rightarrow 2^{\mathbb{E}}$ is the active event function; x_0 is the initial system state; $\mathbb{X}_m \subseteq \mathbb{X}$ is the set of marked states. In the present application, each system state $x \in \mathbb{X}$ is either a collection of node values at a particular instance after an initiating failure occurs or the initial state itself. Every event $e \in \mathbb{E}$ represents a previously nonexistent fault effect. Notice that the precedence order of these events must be consistent with the basic assumption mentioned above. The active event function $\Gamma(x)$ is used to specify the events which could change the system state x, while the transition function $f(x,e)$ is used for stipulating the resulting state caused by $e \in \Gamma(x)$. Finally, it should be noted that the initial state x_0 in this study is always associated with the *normal* condition and the set $\mathbb{X}_m$ contains the final steady states reached in all possible fault propagation scenarios.

To facilitate illustration of the automaton construction steps, let us consider the most fundamental digraph configuration, i.e., tree. More specifically, let us use the fictitious SDG model in Figure 1 as an example and also assume that a positive deviation in the upstream variable d, i.e., $d(+1)$, is the only possible fault origin in this case. Notice that, although the precedence order of any two effects along the same branch path in this digraph can be uniquely identified with the proposed qualitative simulation procedure, the order of two distinct events located on *separate* branches should be considered as indeterminable. The corresponding automaton can thus be described with the state transition diagram presented in Figure 2. Every system state here is characterized with a collection of the qualitative values of all variables in the digraph and all of them are listed in Table 1. Three equally possible event sequences between the initial and final system states can be identified from this automaton model, i.e.,

1. $d(+1)x(+1)y(+1)z(\text{-}1)u(+1)$,
2. $d(+1)x(+1)y(+1)u(+1)z(\text{-}1)$,
3. $d(+1)x(+1)u(+1)\ y(+1)\ z(\text{-}1)$.

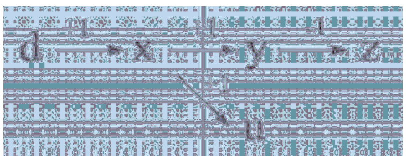

Fig. 1. A tree-shaped SDG model.

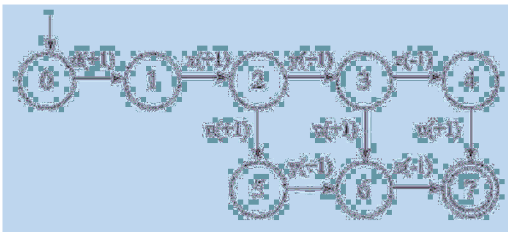

Fig. 2. The state transition diagram of automaton derived from Figure 1.

The automaton resulting from a "large" disturbance can be obtained by following a similar procedure. An auxiliary assumption is introduced in this work to facilitate an accurate description of the fault propagation mechanism, i.e., *the smaller deviation of a process variable must occur before*