

# QUALITATIVE METHODS FOR FAULT DIAGNOSIS

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## Summary

This chapter explains how faults in a dynamical system can be diagnosed if only rough measurements and only qualitative models are available. The rough measurements provide intervals or symbolic signal values. Qualitative models refer to symbolic parameter and signal values. Two methods are explained to show the main ideas of qualitative diagnosis.

First, the General Diagnostic Engine uses a qualitative model of the static system behavior, which is given as a set of logic formulae. Second, diagnosis of discrete-event systems is explained for systems described by nondeterministic automata. Extensions of these and other methods are outlined.

## 1. Introduction

The existing approaches to process diagnosis can be distinguished according to the on-line information and the dynamical models that they use:

- **Diagnosis with quantitative models:** If the process outputs can be measured quantitatively and if the system under consideration can be represented by a

quantitative model in form of a differential or difference equation, the diagnostic task can be solved by identifying the current process parameters or by observing the current outputs or states. Diagnostic methods that use quantitative models are explained in *Fault Diagnosis for Linear Systems* and *Fault Diagnosis for Nonlinear Systems* on Fault Diagnosis of Linear and Nonlinear Systems respectively.

- **Diagnosis with qualitative models:** If the process behavior can be observed merely as a sequence of events a discrete–event description of the system under consideration is used and the diagnostic task is solved by comparing the observed event sequence with the discrete–event dynamics of the model. Different approaches have been elaborated in the fields of Artificial Intelligence and Control Engineering. If the system behavior is described by a knowledge base consisting of a set of rules, constraints or logic formulas, the diagnostic algorithm is based on knowledge processing. On the other hand, if the process model has the form of a Petri net or an automaton, analysis methods from discrete–event systems theory can be used for diagnosis.

This chapter gives a survey of the second class of diagnostic methods, which use qualitative measurement information and qualitative models. These methods have been elaborated by two separate groups of researchers. In the field of Artificial Intelligence, methods for qualitative reasoning are applied to diagnostic problems. On the other hand, in the field of Control Engineering, methods for dealing with discrete–event systems are extended to tackle diagnostic tasks. Two methods described in Sections 4 or 5, respectively, show the main ideas of these lines of research.

**Motivation:** In order to understand the necessity of qualitative methods for fault diagnosis, note that the alternative quantitative methods are applicable only if the following three assumptions are satisfied:

- A quantitative model of the system is available.
- The model parameters are known or can be identified.
- Numerical information about the input  $u$  and output  $y$  can be obtained by measurement.

There are several practical circumstances under which these assumptions cannot be satisfied:

- For complex systems an analytical model is not available or is too complex to be used in diagnosis. Such systems are currently supervised by a human operator who has to find the fault by means of his experience about the process behavior. Such experience does not refer to quantitative measurements but includes assertions about operating conditions or sequences of operating points, which can be represented by sequences of symbols. Typically, process diagnosis uses alarm messages rather than numerical measurement data. If this diagnostic way should be gone automatically, models that refer to the qualitative system behavior have to be applied.

- Many signals cannot be precisely measured as, for example, the biomass concentration in bioreactors, substance concentrations in the liquid or the gaseous phase, the temperature in cement kilns or blast furnaces. Therefore, the diagnostic algorithm has to process quantized measurements rather than real-valued signals.
- Many faults change the behavior of the system severely. Hence, diagnosis can be based on a qualitative description of the system.
- Programmable logic controllers react on discrete changes of measured signals and switch the inputs between discrete values. Hence, a model that refers directly to symbolic signal values is quite appropriate for the diagnosis of such systems.

Under these circumstances it is reasonable to pose the diagnostic problem in terms of symbolic measurement information and symbolic models of the dynamical system under consideration. The common aspect of these and similar situations is the fact that the signals describing the behavior of the dynamical system are not referred to by their numerical values, but by symbolic values that provide a global assessment of the numerical signal value.

Depending on the modeling approach different kinds of symbolic signal information is used. Some approaches use quantized information of the signal and possibly of the signal derivatives (often referred to as qualitative state in the literature on qualitative reasoning), others use symbolic information about the signal form over a given time window or *events*, which denote significant changes of the numerical signal value.

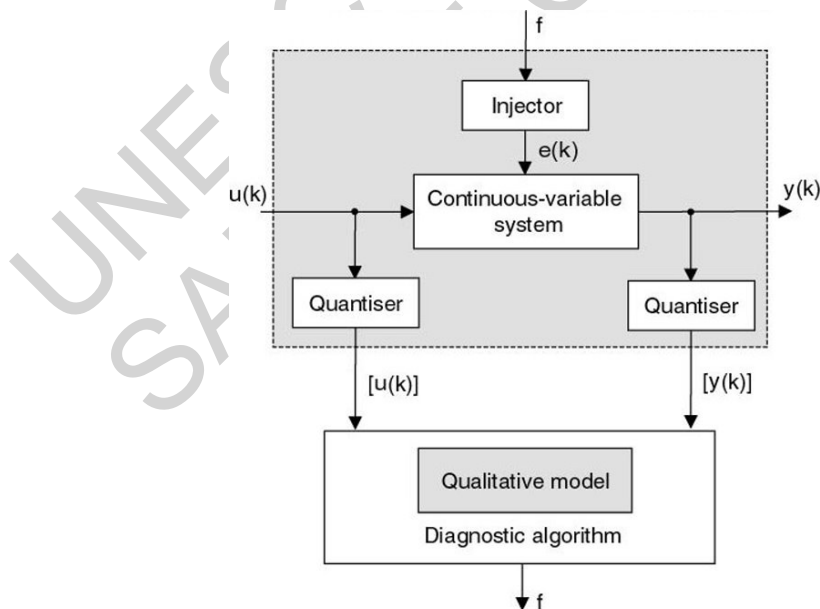


Figure 1: Qualitative diagnosis of dynamical systems

**Diagnostic problem:** Under the practical circumstances explained so far, a standard situation is shown in Fig. 1. The system under consideration is a continuous-variable

discrete–time system

$$x(k+1) = g(x(k), u(k), f), \quad x(0) = x_0 \quad (1)$$

$$y(k) = h(x(k), u(k), f). \quad (2)$$

with state  $x \in \mathbb{R}^n$ , input  $u \in \mathbb{R}^m$  and output  $y \in \mathbb{R}^r$  whose behavior depends on the fault  $f \in F$  where the set  $F$  includes all faults to be diagnosed. The restrictions concerning the measurability of the input and output signals are reflected by the fact that the input  $u$  and the output  $y$  are accessible only through quantizers, which measure the sequences  $[U]$  and  $[Y]$  of quantized input and output values.

The fault  $f$ , which is represented by a symbolic value, is transformed into a numerical value  $e(k)$  by the injector. The symbolic and the numerical value  $f$  and  $e$  of the fault generally depend upon time  $k$ , but they are assumed here for simplicity of presentation to be constant. The grey block in Figure 1 is called a *quantized system*. A crucial idea of process diagnosis is to use a model  $M$  that directly refers to the quantized signal values  $[u(k)]$  and  $[y(k)]$ . The methods differ concerning the kind of model they use.

Artificial Intelligence methods use a static relation among the current qualitative signal values, which is represented by logic formulas as shown in Section 4 or by similar other methods like rules or constraints.

Methods developed in Discrete–Event Systems Theory describe the quantized system by an automaton or a Petri net, which will be explained in Section 5. Both methods solve the following diagnostic problem by comparing the observed event sequence with the discrete–event dynamics of the model, where  $k_h$  denotes the time horizon:

### Diagnostic Problem

Given:        Sequence of qualitative inputs  $[U(0 \dots k_h)] = ([u(0)], [u(1)], \dots, [u(k_h)])$   
                  Sequence of qualitative outputs  $[Y(0 \dots k_h)] = ([y(0)], [y(1)], \dots, [y(k_h)])$   
                  Qualitative model  $M$  of the continuous–variable system  
 Find:        Fault  $f$

**Example:**    In the batch process depicted in Fig. 2 only quantized tank level information is available. The task is to detect the faults like the blockage of valves.

The reduced sensor information introduces a partition of the state space, where the state variables  $x_1$  and  $x_2$  are the two tank levels. Due to this quantization, only six different qualitative states can be distinguished as it is shown in Figure 3.

The diagnostic problem is to find the fault by means of the quantized measurement information, that is, by only knowing in which region of the state space the system currently is.

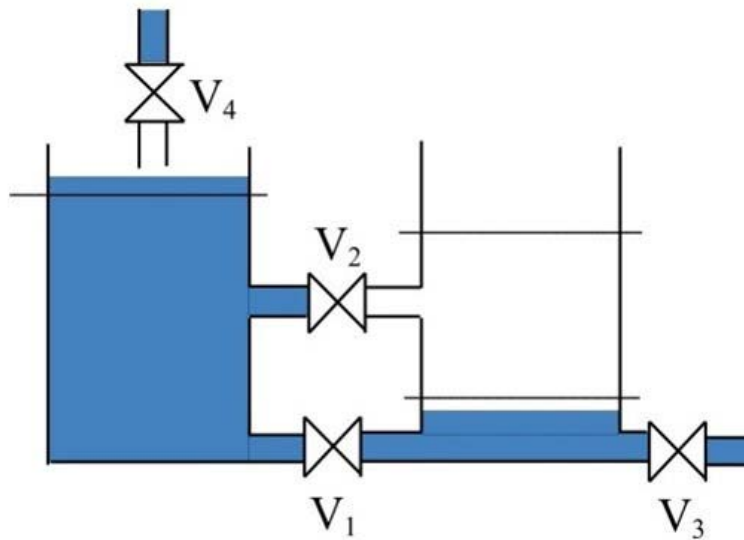


Figure 2: Diagnosis of a batch process

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### **Biographical Sketch**

**Jan Lunze** was born in Dresden, Germany. He obtained the diploma in Automatic Control at the Technical University Ilmenau in 1974. From 1974 until 1992 he was research associate and later Professor of Automatic Control at the Academy of Sciences in Dresden. 1980 and 1983 he obtained the PhD and the DrSc. degrees (Habilitation) both from the Technical University Ilmenau. From 1992 until 2001 he was Professor of Control Engineering at the Technical University Hamburg–Harburg and since 2002 he is head of the Institute of Automation and Computer Control of the Ruhr-University Bochum, where he teaches systems and control theory. Professor Lunze's research interests are in linear control theory, particularly in the fields of robust control and large-scale systems, in hybrid systems, discrete-event systems and in applications of knowledge processing to dynamical systems. Currently, his research is focused on qualitative modeling, fault diagnosis and process control applications of robust and decentralized control. He is author and co-author of numerous papers and of several books including *Robust Multivariable Feedback Control* (Prentice–Hall 1988), *Feedback Control of Large–Scale Systems* (Prentice–Hall 1992), *Künstliche Intelligenz für Ingenieure* (Oldenbourg 1994) and *Regelungstechnik* (Springer 1996).