Annals of Nuclear Energy 97 (2016) 7–26

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Implementation of an integrated real-time process surveillance and diagnostic system for nuclear power plants

Wenlin Wang, Ming Yang *

Fundamental Science on Nuclear Safety and Simulation Technology Laboratory, Harbin Engineering University, Harbin 150001, China

ARTICLE INFO

Article history:
Received 2 December 2015
Received in revised form 27 May 2016
Accepted 1 June 2016
Available online 28 June 2016

Keywords:
Fault diagnosis
Multilevel Flow Model
Observation points' protection
Minimal root cause
G2 expert system

ABSTRACT

This paper presents two parts, real-time process surveillance unit and fault diagnosis unit, which are separated from each other. However, these units are connected by trigger-rules in a real-time expert system. The design structure that has been adopted is capable of inspecting errors and revising the model.

Multilevel Flow Model (MFM), which is a method for functional modeling, is introduced briefly and illustrated with a reactor coolant system. Utilizing functional modeling method to represent system knowledge, this modeling method is especially useful when the domain experts are not available.

Considering issues such as loop modeling and mutually exclusive events inevitably exist between the observation points, a novel modeling technology called observation points' protection was used to build a generic fault model and preserve the statuses of observation points during reasoning within an expert system. This paper also presents minimal candidate and domains of interpretation, which are especially useful for finding the fundamental root cause when multiple faults occur.

The process surveillance and diagnostic system is implemented on the platform of G2, which is an environment for developing real-time expert systems. The emulation test was conducted and it has been proven that the fault diagnosis expert system can identify the faults correctly and in a timely manner.

1. Introduction

In order to meet the increasing energy needs in the world, current and future widespread usage of nuclear reactors depend mostly on the safe and cost-effective utilization of nuclear systems and operational strategies (Pang and Xia, 2014). Developing diagnostic methodologies have become increasingly significant for nuclear power plants (NPPs) in order to provide smooth and uninterrupted plant operation in the face of varying power demand (Ablay and Aldemir, 2013).

Faults are any unpermitted deviations in one or more of the characteristic properties of the system from the acceptable, usual and standard conditions (Yellapu et al., 2015). Fault detection and diagnosis can be broadly classified into methods that utilize qualitative model-based methods, quantitative model-based methods, and process history based methods (Venkatasubramanian et al., 2003). Model-based methods require a priori knowledge about the domain as well as the relationships between the distinct patterns of fault evolution and the different faults (Du and Van, 2012). Accordingly, analytical model-based methods can be difficult to implement for systems with complex nonlinear dynamics, and are mostly limited to linear applications or linear model approximations (Evsukoff and Gentil, 2005). In contrast to the model-based approaches where a priori knowledge (either quantitative or qualitative) about the process is needed, in process history based methods, only the availability of large amount of historical process data is needed, and one of the major methods that extract qualitative history information is the expert system.

The approach of the expert system has become the most popular branch of artificial intelligence, which aims to design a fault diagnosis system. For the expert system, an advantage is the independence of detailed knowledge of plant behavior. However, a disadvantage is that fault situations are defined by patterns of observed plant variables values (Lind and Zhang, 2014). There is difficulty in acquiring and representing the knowledge correctly, it may accordingly be difficult to diagnose faults which have not been encountered before (Hong et al., 2010).

Under this circumstance, the functional modeling method is introduced. A functional modeling method called Multilevel Flow Model (MFM) was utilized to represent the knowledge of the system, especially when the domain experts are not available. Meanwhile, the combination of the MFM and expert system constituting as the domain map that can serves as input to the reasoning

* Corresponding author.
E-mail addresses: wlwang0618@126.com (W. Wang), myang.heu@gmail.com (M. Yang).

http://dx.doi.org/10.1016/j.anucene.2016.06.002
0306-4549/

machine. In this way, it is easier for developers to design the knowledge base and develop a fault diagnosis expert system. This viewpoint has also been mentioned in authors' previous article (Wang et al., 2016).

However, with the growth of the acquired knowledge, the issues of loop modeling and mutually exclusive events inevitably exist in the generic fault model, but these are not considered in the previous work.

In order to describe above-mentioned issues, for example, the parameters that are used in NPPs can divided into two categories; these are observed points and unobserved points. The observation points, that is, their statuses are specified. They cannot be changed, which has been confirmed during reasoning in the expert system.

However, some observation points are mutually exclusive events, meaning that they cannot happen at the same time. Further, loop modeling serves as one relationship also exist between some observation points. In this case, the statuses of observation points may be changed during reasoning in the expert system.

Within this context, one kind of modeling technology, the observation points' protection modeling, was used for protecting the statuses of observation points and solving loop reasoning within a generic fault model. The observation points' protection technology will be explained in detail in Section 4.4.2.

As for the multiple faults and the occurrence of many symptoms, it is necessary to identify the genuine faults, or fundamental root cause, from the suspect candidates. Inspecting the causal chain is one method to find the fundamental root cause. However, it is too cumbersome for operators to do this all the time.

Within this context, this paper presents the minimal candidate that can identify the fundamental root cause or their combination automatically. The detailed explanation of the minimal candidate will be presented in Section 6.

The integrated real-time process surveillance and diagnostic System (RTPSDS) was implemented on the platform of the G2 expert system. Gensym's flagship G2 expert system is the world's leading real-time engine platform (Gensym Corporation, 2009).

This rest of the paper is organized as follows: In this section, the background and motivation are presented. Section 2 provides a brief description of the MFM. Section 3 is devoted to describing the expert system. In Section 4, there is a description on how to design a real-time process surveillance and diagnostic system by utilizing the MFM and G2 expert system, including the framework of RTPSDS described in Section 4.1, the design of process surveillance described in Section 4.2, the design of trigger rules described in Section 4.3, and how to design a fault diagnosis unit as described in Section 4.4. In this section, the combination of MFM and expert system and the modeling technology of observation points' protection are introduced. The simulation tests are presented in Section 5, while the design of the minimal candidate is discussed in Section 6. The conclusions of this work are presented in Section 7.

2. Multilevel Flow Model

2.1. Basic theory of MFM

The Multilevel Flow Model (MFM) is a methodology for modeling industrial processes on several interconnected levels of means and part-whole abstractions. The basic idea of MFM is to represent an industrial plant as a system which provides the means required to serve purposes in its environment (Lind, 1994, 2011a,b). The MFM represents the goals and functions of process plants involved in the interactions between the flows of mass, energy, and information (Lind, 2011a,b). It describes the system goals, functions, and components needed to model the process of plants by using some specific graphical symbols (Yang et al., 2014). The symbols of MFM are as shown in Fig. 1.

In the MFM, the goals are the basis of modeling thought to realize the functions of each part of the system, such as "supply electricity". and the function nodes consisting of functions relate to goals to represent the capabilities of a system, for example, "transport coolant", while the components represent the physical structures of a system, such as a piece of pipeline. After being invented by Lind (1990) at the Technical University of Denmark, MFM has been proven to be effectively contributing to several diagnostic algorithms, such as measurement validation, alarm analysis, failure model analysis, sensor fault detection, and fault diagnosis (Öhman, 1999, 2001, 2002; Dahlstrand, 1998; Larsson, 1996).

3. Expert system

Artificial Intelligence (AI) is that branch of computer science that seeks, in some measure, to emulate human behavior, while expert systems are a special type of computer software for which the objective is to reproduce the capabilities of an exceptionally talented human or groups of humans (John and Takashi, 1989). This is achieved by encoding human experience in various knowledge representation schemes. Expert systems differ from conventional algorithmic programming in two aspects.

(1) As new information is obtained, it can be added to the knowledge base without revising the inference engine. That is, no reprogramming is needed.
(2) An expert system can at any time provide the rationale for its conclusion. It does this by keeping track of the chain of deductions that supports each particular conclusion.

In conclusion, the main advantages in development of expert systems for diagnostic problem-solving are: ease of development, transparent reasoning, the ability to reason under uncertainty and the ability to provide explanations for the solutions provided.

The main components in an expert system development include: knowledge acquisition, choice of knowledge representation, the coding of knowledge in a knowledge base, the development of inference procedures for diagnostic reasoning and the development of input–output interfaces (Venkatasubramanian et al., 2003). However, the key element of the expert system is knowledge base, which contains two aspects: knowledge acquisition and knowledge representation. The knowledge acquisition mainly acquires knowledge from domain experts and it is one of the most difficult and time-consuming activities in developing knowledge-based systems. The premise of designing an excellent

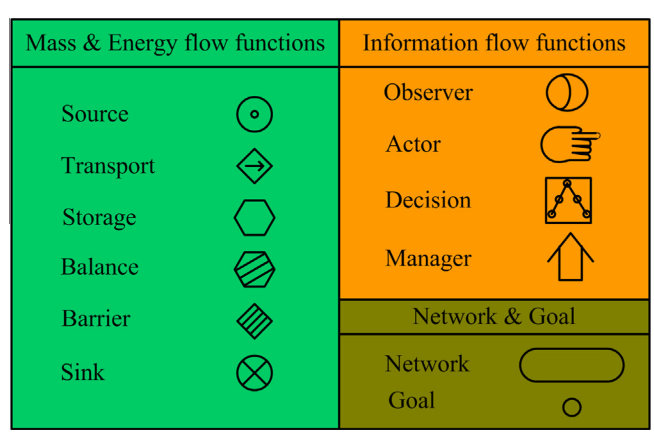

Fig. 1. Symbols of Multilevel Flow Model.