**A DIAGNOSTIC HIERARCHY APPROACH TO
ROOT CAUSE ANALYSIS
FOR HEAVY WATER REACTOR MALFUNCTION MANAGEMENT**

Final Report

by

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1.0 INTRODUCTION

This report summarizes the research accomplished made under the Department of Energy Office of Energy Research Special Research Grant Program in Nuclear Engineering through the DOE-ER Nuclear Engineering Education Research Program grant number DE-FG07-90ER13028.

In Chapter 1, we present an introduction and background material for the operator advisor research undergoing at The Ohio State University. We then discuss the original project goals and explain why they changed throughout the project.

In Chapter 2, we outline our methodology for achieving the proposed goals and describe the verification and validation program that we used to guide our project development. The original diagnostic system architecture is presented along with the changes that we have implemented. Next, a discussion of knowledge acquisition and knowledge representation is given; and lastly, we will describe the testing that was performed and present their results.

In Chapter 3, we list the educational benefits that resulted though this project and give a brief description of the technical papers and resulting master thesis.

1.1 Background

In February of 1990 a proposal was submitted to investigate designing a diagnostic operator aid for the heavy water reactors at the Savannah River Site (SRS). At that time the Scientific Computations Section (SCS) at the SRS was designing an Intelligent Reactor Information System (IRIS). The faculty and students in the Nuclear Engineering Artificial Intelligence (AI) Group at The Ohio State University (OSU) had been developing an Operator Advisor (OA) for the Perry Nuclear Power Plant using a diagnostic hierarchy approach [1,2]. The original proposal outlined a joint effort between the Nuclear Engineering AI Group and the Chemical Engineering AI Group at OSU to design and integrate a heavy water reactor version of this diagnostic system into IRIS. It was expected that this integrated AI based information system would be included in the design of the New Production Reactor. Following initiation of this research, the New Production Reactor was canceled and IRIS was put on hold.

In response to the changing needs at Savannah River, we modified our original objective of designing a system to merge with IRIS to that of developing a "stand alone" version of the diagnostic expert system for the Heavy Water Reactor (HWR) facilities located at the Savannah River Site (SRS). The emphasis on this new objective was to complete a "Text Book" design, development and evaluation of this system. Since software is increasingly being used to perform various tasks at nuclear power plants and for other applications where safety is a critical issue, there is an effort to specify the design and testing requirements for this safety critical software. ANSI-IEEE has developed several standards to use for guidelines [3,4,5,6] and EPRI has published several reports to assist in developing expert system software [7,8]. The new goal was to use these standards and reports to design an expert system and to document the design and development to provide guidance for future design projects.

The purpose of the expert system was to assist the human operator in effectively maintaining plant safety and to enhance plant reliability. Although the design changed to that of a stand alone unit, it still used a hierarchy based diagnostic architecture similar to that of the Operator Advisor.

1.2 Discussion of Goals and Objectives

Although the plans to integrate the diagnostic system into IRIS were canceled, several of the initial goals remained. First, in conjunction with SRS personnel the research plan was refined. Next, plant specific knowledge was acquired through close interaction with SRS personnel. One or two systems were then selected for further analysis, these systems were decomposed into a diagnostic hierarchy, and scenarios were selected to test the system. These goals are summarized into the groups of knowledge acquisition, knowledge representation, and knowledge testing. These three objectives are discussed in depth in the next chapter, along with the methodology used to efficiently conduct the specific tasks.

2.0 PROGRESS IN ACHIEVING GOALS AND OBJECTIVES

2.1 Verification and Validation Plan

Many expert systems, including the OSU Operator Advisor, are built through a rapid prototyping process. Through this process, no formal Software Verification and Validation Plan (SVVP) or Software Requirements Specification (SRS) is developed prior to initial prototyping. This rapid prototyping method gives little or no guidance to the developer in the form of what the software requirements are and how to confirm that the system meets those requirements. It also provides little documented evidence of the ability of the end design to meet any functional requirements. This audit trail is of vital importance in licensing safety critical software. Because of these drawbacks to rapid prototyping, we developed a standardized approach to Verification and Validation (V&V) that we would implement in our "text book" design and development. We used this approach to guide the system development through the design phases and to ensure that the end product fulfilled the initial requirements and project objectives.

The basic function of a V&V program is to ensure the production of a quality software product that is error free and that functions as desired. It performs this function by evaluating the software product at specified stages, from its initial concept to its installation and operation. It verifies the software product at the end of each stage to ensure error free operation (internal correctness), and it validates the software product at the end of the software development to ensure the final product incorporates both the features and functionality as prescribed by the software requirement specifications (external correctness) and most importantly, meets the needs of the user.

We integrated formal V&V procedures with the development of the software product, to realize the following benefits:

1. Earlier and less costly error detection.
2. Improved tracking of the software development by management.
3. Higher software quality and reliability.
4. Better system maintainability.
5. A well defined end product that better meets the initial objectives.
6. A more structured and focused development environment resulting in more efficient development.

The IEEE Standard for Software Verification and Validation Plans (SVVPs) was used to construct the SVVP for the new system. This plan outlines the V&V tasks necessary to verify the product at the end of each software life-cycle phase, and to validate that the end product complies with the established software and system requirements [3]. The IEEE Guide to

The design phase is the period of time in the software life-cycle during which the designs for architecture, software components, interfaces, and data are created, documented, and verified to satisfy the requirements stated in the previous phase. The V&V tasks verified that the design met the requirements stated in the Software Requirements Specification and verified that specific tests were made to test each requirement and design.

The expert system for HWR diagnosis is composed of six distinct design entities that reside on a SUN IPC SPARCstation as shown in Figure 3. The data link communicates data requests to a data server, and receives data from the data server as required for the operation of the expert system. On site at SRS, the data-server is a Symbolics 3645 LISP machine interfaced with the Gould simulator via a high speed parallel data bus link. The SUN IPC communicates its data requests over an ethernet to the Symbolics through remote procedure calls, and receives data packets as requested. At OSU, a SUN SPARCstation 330 emulates the Symbolics machine and serves the data requests from precollected data files. Using this emulation setup, a proper malfunction data set is chosen and the same remote procedure call is used by the IPC to access the data over a similar ethernet. This arrangement makes the data server transparent to the diagnostic system; the diagnostic system does not know if it is being served by the simulator or if it is being served from a precollected data file residing on the SUN 330.

Figure 3. System Architecture

Data is transferred over the data link at a desired sample rate and is written into a section of memory called shared memory. This memory segment is accessible by other processes and is the fastest means of internal process communication on the SUN. This high-speed database is used to store the data for later retrieval. The data is time stamped with the actual simulation time which is transferred across the data link with the data pack. The data is saved for a specified time period. This results in the ability to access the complete history of parameter variations for use in detecting deviations from normality and for use in diagnosing the deviation.

The basic function of the data abstraction module is to convert raw data into a more usable form. It does this by accessing raw data from the database, performing functions on this raw data, and then returning the result to the monitoring or diagnostic modules. This module is actually composed of many smaller modules that perform computations such as trend analysis, and limit checking. The results can be quantitative, such as 5 [degrees/minute], or qualitative, such as quickly increasing. Examples are: the number of running pumps, alarm status, heat up rates, and valve positions.

The basic function of the monitoring module is to monitor certain critical plant parameters and identify abnormal changes. It performs this function by first querying the shared memory database for predefined plant parameters and then comparing them to predefined limits. This monitoring process is continuous while at power and only stops if a deviation is detected and diagnosis has been initiated.

The basic function of the diagnostic module is to find the root cause of any deviation from normality. First it receives an initiation message from the monitoring module, then it prunes the search space using an

We interviewed reactor operators, reactor training personnel, and reactor engineers to determine both the plant response and the operator response to simulated Process Water malfunctions. We participated in malfunction walk-throughs at the full function simulator and observed reactor operator crews manage the malfunctions. We documented the indicators that were consulted, the sequence of actions taken, and the results of those actions. This documentation provided us with a detailed list of the key indications and parameter variations that occur during the simulated malfunctions.

Next, we ran malfunction scenarios on the engineering simulator and compiled a list of plant parameter trend variations. We expanded the original list to include all parameters that varied, even if they were not used by the operators to perform diagnosis. To obtain a hard copy of the reactor parameter variations, we connected a data link between the engineering simulator and a SUN IPC SPARCstation. Over two hundred and fifty data points were transferred every second over an ethernet and written to a data file.

We collected a five minute data file for each malfunction scenario, graphed the plant parameters, and analyzed them to determine expected and unexpected trends. The analysis of these trends combined with the diagnostic methodologies employed by the operators provide the basis for the hierarchy construction. We also saved the data files to disk to be used at OSU to emulate the data transfer of the simulator, this simulator emulation will be explained later.

2.5 Knowledge Representation

After gathering knowledge on how the system and the operators respond to malfunctions, the knowledge was organized into a malfunction hypothesis hierarchy. In this hierarchy, the top nodes represent more general malfunction hypotheses while the lower levels correspond to more specific malfunction hypotheses. The bottom level nodes, called tip nodes, map to the root cause of the malfunction.

The hierarchy is traversed in a top down fashion with an establish-refine methodology. Knowledge is represented in the hierarchy with data groups that are attached to the malfunction hypothesis nodes. These knowledge groups represent patterns of data that either establish or reject the malfunction hypothesis at a specific node. A malfunction node is established if the plant data matches the pre enumerated pattern that identifies that malfunction. If a malfunction node is established, its children nodes are examined to refine the hypothesis. If a malfunction node is not established, then its children nodes are ruled out also. This methodology prunes the search space by ruling out entire branches of the hypothesis space, thus speeding the diagnostic process.

The tool originally chosen to implement this control strategy is CSRL (Conceptual Structures Representation Language). CSRL was developed by The Ohio State University Laboratory of Artificial Intelligence Research (LAIR) in 1983 to be used for classificatory problem solving [2]. It is a LISP-based tool, but calls C functions to access the plant data. CSRL was replaced with a similar tool written in C++. The system was upgraded to C++ for the following reasons:

1. CSRL had a compilation time of 20 to 30 minutes for knowledge groups as large as ours. This meant that every time a change was made to a knowledge group, the entire hierarchy was recompiled creating a 20 to 30 minute delay. With C++ this delay was reduced to about 30 seconds.

Figure 5. Functional Based Decomposition

would determine if the system actually helps the operators detect and diagnose process water malfunctions. This testing was made impossible due to the unavailability of the full function simulator and the lack of hardware and software necessary to hook up the data link.

3.0 SUMMARY

The Nuclear Engineering and Chemical Engineering Artificial Intelligence Groups at The Ohio State University have developed a diagnostic system for the heavy water production reactors at the Savannah River Site.

The diagnostic module of the system uses hybrid hierarchical decomposition methodology to decompose the search space. The knowledge is arranged so that the search space is traversed similarly to how an expert would solve the problem. The system was tested on the SRS development simulator and the results show that the system can properly diagnose all the process water and cooling water malfunctions that are programmed into the simulator. The system was not validated by operators due to hardware unavailability. Since the New Production Reactor development efforts have been halted, the probability for future work on this project is unlikely.

The development used a standardized Verification and Validation program to assist in the design and construction of the system. The use of this standardized procedure is referred to as a "text book" example of designing an expert system in the expectation that its use would provide guidance in future projects.

Of the eight phases of the software development lifecycle, five of the phases were completed and documented. The lifecycle began with the concept phase where the user's needs were determined. During the requirements phase the software requirements specification was developed to meet the user's needs and a software test plan was written to test those specifications. The design phase led to the development of a software design description which met the specifications. During the system implementation and testing phase, the components were tested and integrated to form a diagnostic system which was also tested. Knowledge was entered and tested in the knowledge representation and testing phase. The validation phase was not performed because of limitations on site as discussed above and the system implementation and testing phase and the operation and maintenance phase were not completed.

Although the system was not validated or installed and used, the standardized approach to the design and development proved useful throughout the development process. It provided guidance and direction to the development team and provided the management oversight committee with a checklist that was helpful in fulfilling their function. Lastly it provided an audit trail that documented what was completed, what errors were found, how the errors were corrected, what decisions were made and why those decisions were made. This audit trail would be useful to the design of a similar product and it would also be useful for the technical investigations that may be performed by a licensing committee.

One important requirement of a V&V system that was not implemented was that there was no separation of the design and V&V personnel. This was due to the limited personnel assigned to the project. Although the management committee who reviewed the V&V documents was separate, the internal V&V audits and testing were performed by the same personnel that designed and implemented the diagnostic system. This may have limited the effectiveness of the V&V effort, but however limited it may have been, the system still proved extremely valuable.

4.0 EDUCATIONAL ACHIEVEMENTS

This grant provided research support for several graduate students, and a provided a basis for four Master's of Science degrees in Nuclear Engineering. A brief summary of these thesis are included below.

Wes Hines spent his DOE practicum at the Savannah River Site working for the Scientific Computations Section in designing and implementing the diagnostic system. He conducted the knowledge acquisition and knowledge representation tasks for the process water portion of the system. He designed and tested the initial system and supervised the V&V tasks. His masters was earned in Spring 1992.

Martin Hass's thesis titled "A Knowledge Based System for the Diagnosis of Cooling Water System Malfunctions in a DOE Production Reactor" (Autumn 1992) centered on the diagnosis of cooling water malfunctions in the K-Reactor. He used real time simulation data in the development and verification of the diagnostic system.

Lane Robbin's thesis titled "An Object Oriented Implementation of a Knowledge-Based System Designed to Diagnose Malfunctions in a Heavy Water Reactor" (Autumn 1992) was concerned with the conversion of the original LISP based system to a C++ based system. The new expert system design implemented in C++ is composed of three main components: a knowledge base, an inference engine, and user interface facilities. An inference engine which takes advantage of the class structure provided in C++ was designed to traverse the hierarchy. A user interface facility was designed to display the on-line monitoring window as well as a message window which displays the results of the diagnosis when an abnormality is detected. Finally, the system was tested through the use of a plant simulator. This testing indicated that all of the simulated malfunctions available could be detected and diagnosed with this system design. This system design also has proven to offer many advantageous over the LISP-based system. It is fully functional with the Unix Operating System and the X-Window system which allows for direct correspondence with system calls and library subroutines. The compilation time is on the order of seconds as opposed to 15 - 20 minutes for the LISP-based system. Thus the new system was proven to be much more maintainable.

Satoru Kiyohashi's thesis titled "An Improved Implementation of a Knowledge Based System for the Diagnosis of Malfunction in a Commercial Boiling Water Reactor" (Spring 1993) expanded on the system improvements made by Lane Robbins. Although he used a boiling water reactor as the reference plant, the improvements were made available to the SRS system. The improvements included a better user interface with browsers, a high modularity of programs, a complete separation of the knowledge base from the inference engine and other routines, and the capability to handle multiple malfunctions.

In addition to these four Nuclear Engineering master's theses, this research also contributed to two Chemical Engineering Ph.D. dissertations: James K. McDowell's dissertation was titled "The Integration of Model-Based Reasoning and Task Specific Problem-Solving Architectures for Chemical Process Diagnosis" (1991), and Prasad Ramanathan's dissertation was titled "Diagnostic Knowledge-Based Systems for Continuous Chemical Processes: Enhanced Knowledge Acquisition & Generic Problem-Solving Framework" (1993).

Several technical papers were presented at technical conferences and published in the their respective proceedings [11,12]. Copies of these papers are included as Appendix 6.3.

5.0 REFERENCES

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12. Hines, J. W., D. W. Miller, B. K. Hajek, "A Hierarchical Paradigm for Root Cause Analysis of Process Water Malfunctions in a Heavy Water Reactor Facility", presented and published in the proceedings of the 8th Power Plant Dynamics Control & Testing Symposium, Knoxville, TN., May 27-29, 1992.

6.0 APPENDIX

6.1 V&V Documents

Software Verification and Validation Plan

Software Requirements Specification and Design Description

Software Test Plan

6.2 Master's Theses

Martin Hass's thesis abstract titled "A Knowledge Based System for the Diagnosis of Cooling Water System Malfunctions in a DOE Production Reactor"

Lane Robbin's thesis abstract titled "An Object Oriented Implementation of a Knowledge-Based System Designed to Diagnose Malfunctions in a Heavy Water Reactor"

Satoru Kiyohashi's thesis abstract titled "An improved Implementation of a Knowledge Based System for the Diagnosis of Malfunction in a Commercial Boiling Water Reactor"

6.3 Ph.D Dissertations

James K. McDowell's dissertation abstract titled "The Integration of Model-Based Reasoning and Task Specific Problem-Solving Architectures for Chemical Process Diagnosis"

Prasad Ramanathan's dissertation abstract titled "Diagnostic Knowledge-Based Systems for Continuous Chemical Processes: Enhanced Knowledge Acquisition & Generic Problem-Solving Framework"

6.4 Published Papers

1. J.W. Hines, B.K. Hajek, D.W. Miller and M.A. Haas, "A Standardized Approach to Verification and Validation to Assist in Expert System Development". Presented and published in the proceedings of the EPRI Conference on Methodologies, Tools, and Standards for Cost Effective, Reliable Software Verification and Validation, Chicago, IL, August 1991 and EPRI Conference on Expert System Applications for the Electric Power Industry, Boston, MA, September 1991.

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3. J.W. Hines, B.K. Hajek, D.W. Miller, "A Hierarchical Paradigm For Root Cause Analysis of Process Water Malfunctions in a Heavy Water Reactor Facility," published and presented at the 8th Power Plant Dynamics, Control & Testing Symposium Proceedings, Knoxville, Tennessee, May 29, 1992.

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