ARE MAINTENANCE EXPERT SYSTEMS PRACTICAL NOW?

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CUCS-166-85
166(A)

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Abstract: This paper examines the question of whether Artificial Intelligence expert system technology can be effectively applied to real world maintenance problems. Expert maintenance systems installed to date are reviewed and the ACE (Automated Cable Expertise) knowledge-based expert system presently marketed by AT&T is described in detail.

ACE provides timely trouble-shooting reports and management analyses for telephone cable maintenance. Many design decisions faced during the construction of ACE were guided by experience gained in the development of previous expert systems. The most significant departure from "standard" expert system architectures, however, is ACE's use of a conventional data base management system as its primary source of information. Its primary sources of knowledge are the expert maintenance personnel, who previously were users of the database system, and primers on maintenance analysis strategy. The coupling of "data base" and "knowledge-base" demonstrates in a forceful way the manner in which an expert system can significantly enhance the throughput and quality of automatic maintenance support systems.

Based on the success of these maintenance expert systems, explosive growth of knowledge-based expert maintenance programs is predicted. Forthcoming maintenance expert systems will assist in the repair of high capital cost equipment, for which down time is expensive or unacceptable, or for which competent repair personnel are in short supply.

Key words: Artificial intelligence; AI; Expert systems; Knowledge base; Maintenance.

Introduction: Knowledge-based expert systems are Artificial Intelligence (AI) problem-solving programs designed to operate in narrow "real-world" domains, performing tasks with the same competence as skilled human experts. Elucidation of unknown chemical compounds [Buchanan and Feigenbaum 1978], medical diagnosis [Shortliffe 1976] and mineral exploration [Duda et al. 1979] are three of the best known examples. The heart of these systems is a ***knowledge base***, a large collection of facts, definitions, procedures and

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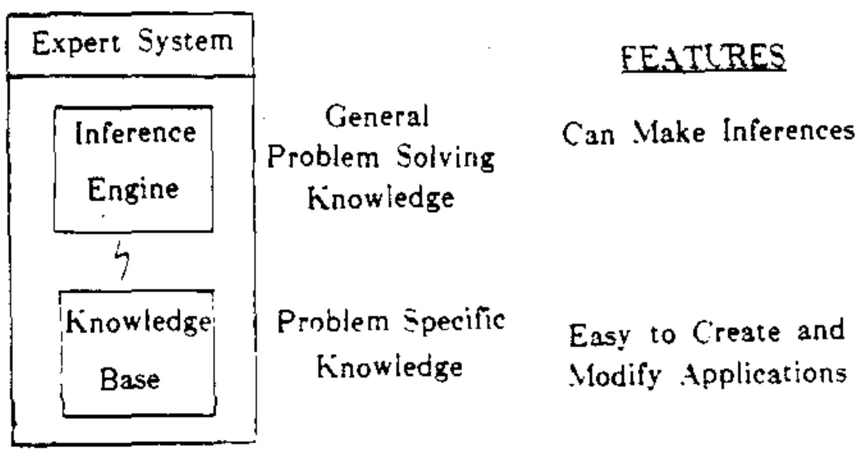
*Partial support provided by Office of Naval Research under Contract N00014-82-K-0256

heuristic "rules of thumb", acquired directly from a human expert.

Current Technology: Knowledge-based expert systems are usually composed of two loosely coupled modules, collectively forming the ***problem-solving engine*** (see Figure 1). The ***inference engine*** is the component of a system which ***controls*** the deductive process; it implements the most appropriate strategy, or ***reasoning*** process for the problem at hand. The ***knowledge base*** contains all of the relevant domain-specific information permitting the program to behave as a specialized, intelligent problem-solver. Much of the research in AI has concentrated on effective methods for representing this knowledge. The representations that have been proposed have taken a variety of forms including purely declarative-based logical formalisms, "highly-stylized" rules or productions, and structured generalization hierarchies commonly referred to as semantic nets and frames.

Figure 1: Organization of a Problem-Solving Engine



The earliest AI problem-solvers were implemented with an iterative branching technique searching a large space of problem states. In contrast, state-of-the-art expert systems separate the control strategy from an inflexible program, and deposit it in the knowledge base along with the domain-specific data. Thus, the problem-solving strategy becomes domain-dependent, and is subject to the same methods of acquisition and deductive manipulation as facts and assertions.

Maintenance Expert Systems: Generically, the maintenance process begins with the detection and diagnosis of a failed or failing item. Next, a recommended course of action is determined. Maintenance Expert Systems (MESs) replace or assist human repair experts in some or all of these three phases. While one usually thinks of maintenance as involving a physical system, this need not be the case. The first MES we will describe, YES/MVS (Yorktown Expert System for MVS operators), is a good example. The system which exerts interactive control over a Multiple Virtual System (MVS) does not perform maintenance on a physical system, but it satisfies the criteria for a maintenance system. Following the section on YES/MVS, MESs for nuclear reactor monitoring, diesel locomotive repair and oil rig maintenance will be described. Finally, a MES for telephone cable maintenance will be described in greater detail.

YES/MVS is a continuous, real-time expert system that exerts interactive control over the MVS operating system as an aid to computer operators [Griesmer et al. 1984]. The MVS operating system running with Job Entry System (JES) prints out hundreds of messages to a computer operator. Some messages flag software, hardware and scheduling (potential) problems. Other messages are purely statistical in nature. The peak message rate from MVS to the operator exceeds 100 a minute, but only a small subset of these messages require an action by the operator. YES/MVS is designed to reduce the load on the computer operator by automatically testing conditions and/or executing actions.

The complex, dynamic nature of a computer system requires real time processing capability. YES/MVS draws conclusions based on primitive facts obtained directly from monitoring the system [Griesmer et al. 1984]. Speed is gained, and inconsistencies that result from actions that are based on conditions which no longer hold, are reduced.

The long training hours and increasing complexity of the computer maintenance task has resulted in a shortage of skilled operators. There are many different computer configurations and each operator is responsible for the configuration requirements and local policies relevant to their particular site. In this volatile environment, the demand on the operator increases as a system changes and grows in complexity. Expert system technology provides the flexibility necessary to easily update information whenever needed. YES/MVS now routinely schedules the queue of large batch jobs, alerts operators of potential overload, and responds with appropriate corrective recommendations. Other task areas are in the final stages of testing.

REACTOR is an expert system that assists operators in the diagnosis and response to nuclear reactor accidents. Control rod positioning determines the rate of nuclear reaction occurring in the containment vessel. Heat in the system is removed by the primary cooling system (PCS), unless a malfunction occurs, at which time the reactor is automatically shut down, and the Emergency Core Cooling System (ECCS) takes over. Cooling must be continued after a shut down in order to remove radioactive decay heat. During an emergency, efficient analysis may terminate incidents without serious consequences, while inappropriate actions may result in severe damage. The Three Mile Island incident demonstrates that the information resources available to an operator during an emergency are sometimes inadequate. The operator received over 100 alarm warnings, and in the face of this extreme overload, misinterpreted the situation, resulting in an inappropriate shutdown of the ECCS.

The purpose of REACTOR is to monitor a nuclear reactor facility, detect deviations, determine the significance of the situation, and recommend an appropriate response [Nelson, 1982]. REACTOR performs according to the expert's knowledge. If information is missing, REACTOR queries the plant instruments or the operators. The function-oriented knowledge in the knowledge base, contains information about the configuration of the reactor system, at the particular site, as well as information on how the components of the plant work together. The event-oriented knowledge describes the expected behavior of the reactor under different conditions. The two types of knowledge encompass almost all potential failures, because the function-oriented knowledge allows the system to reason about situations not explicitly represented in the event-oriented knowledge.

REACTOR currently monitors a simulation. When installed at a real site, REACTOR will receive information, for example temperature and pressure, directly from the plant, and supply some of the on-line analysis required. REACTOR provides effective integration of massive amounts of data, providing consistent interpretations at a fast rate, reducing the time required for diagnosis. The corrective procedures, recommended by REACTOR are executed by the operator. The emphasis of REACTOR has changed from a diagnostic system to a consultation system that helps the operator analyze large quantities of data available during a nuclear accident.* In life threatening situations, it is believed (at least

*Personal communication with W. R. Nelson, February 1985.

for the time being) that final decisions are best left to a human being. Experiments are being conducted with simulated accidents, to determine the differences in performance when an operator has the assistance of REACTOR. At least five additional nuclear related expert systems are under development.

CATS-1 [Marcus 1983] is a system that aides in the troubleshooting and repair of GE diesel locomotives.* Each of the many tasks performed by repair personnel require distinct procedures. These procedures are comprised of heuristic and text book knowledge.

The system is designed for operation on a shop floor by individuals with varying levels of expertise. Users are prompted for information by questions requiring yes/no, or numeric answers. If a repairman does not know how to obtain the requested data, an on-line help system is available. The status of the locomotive is analysed, and instructions for correcting problems are provided. Depending on the nature of the problem, the instructions may be provided in graphic or textual formats, and references to part numbers and maintenance manuals are included when appropriate. The repairman may examine the reasoning employed by the system, and he may request more detailed instructions at any time. As the system contains several distinct sets of explanations and instructions, it provides a natural environment for a training system. In addition to augmenting efficient expeditious repairs, the system functions as a training system and reduces training time required by new personnel.

The DRILLING ADVISOR is designed to assist the supervisor of an oil rig in resolving and eventually avoiding sticking problems [Teknowledge]. Down-hole sticking is a condition in which the motion of the drilling apparatus is impeded. When this occurs, both drilling and tripping (the periodic return of the down-hole equipment to the surface) are stopped. The DRILLING ADVISOR is designed to minimize these extremely costly outages.

The only information relevant to the diagnosis of problems are descriptions of the formations within the exposed open-hole below the protective steel casing of the drill string. The drill string is divided into two parts, the bottom hole assembly (BHA), whose components effect and moderate the cutting process, and the drill pipe which connects the BHA to the surface equipment. The DRILLING ADVISOR functions at a well, problem and episode level. At the well level, the system obtains from the user preliminary information about the well, including vertical position and the constituent rock types of each formation. At the problem level, the system characterizes the circumstances surrounding the onset of sticking by identifying the boundary depths of the open-hole and the type of action performed prior to sticking. At the episode level, the system accommodates the observable symptoms of a particular problem and considers the possible changes over time. This type of analysis permits the system to directly compute contact relationships between formation/element pairs [Teknowledge]. Each episode uses the information accessed by the previous episode until one of the recommendations proves successful.

The process of drilling a production oil well is complex and expensive. Reducing down-time has an enormous impact on cost. The results to date are encouraging. Extending the capabilities of the DRILLING ADVISOR, and integrating it into an actual drilling environment are planned.

A Detailed Example: *ACE* (Automated Cable Expertise) is an automatic analysis system which peruses large volumes of failure reports in a telephone network. In the following, we describe its general function and structure. For more information, the reader is encouraged

*Personal communication with R. Herman, General Electric, Erie Pennsylvania.

to see [Stolfo and Vesonder 1982] for a detailed description of the system.

The Problem: In normal operation, the telephone network supports a telephone line, called a ***cable pair***, originating at a residential or business site. A collection of pairs are bundled together to form the cables that hang from telephone poles, or reside underground. A collection of cables form a ***wirecenter***. General maintenance and rehabilitation of lines are critically important and expensive operations performed by Bell Operating Companies. A variety of electrical faults and environmental conditions can cause failure of one or more cables or individual pairs: insect infestations in terminal boxes and gnawing rodents are perennial problems.

Customer generated maintenance reports provide important information for identifying "trouble spots" within a local network. In a high-density geographic area, the logging and tracking of failure reports has become an important and expensive data processing operation. Thus, many telephone companies use a conventional database system, called *CRAS*, to monitor the maintenance of the local network on a daily basis. Highly trained analysts routinely peruse large volumes of *CRAS* data to identify required maintenance tasks.

CRAS provides a set of report generating programs which produce summaries of various aspects of customer and employee generated maintenance reports. An individual record maintained by *CRAS* consists of numerous fields detailing a problem reported by a customer or employee. This is referred to as a ***trouble*** in telephone company jargon. Many distinct *CRAS* records representing troubles may refer to the same pair or cable, indicating a potential chronic problem.

The large volume of detailed information allows the human expert to perform many analyses and to make an informed selection of candidates for rehabilatative maintenance. However, the limited number of specialists available, and the size of the database inhibit the timely detection and repair of many recurring problems. The approach of installing *ACE*, to assist management decision making, was proposed as a solution to the long-term problem of timely and accurate selection of areas for rehabilitation.

The *ACE* Problem-Solving Engine: Within *ACE*, the knowledge about wirecenters, *CRAS* data and commands, and analysis strategies is captured in a ***Production System*** program. In general, a ***Production System*** [Newell 1973] is defined as a set of rules, or ***productions***, which form the ***Production Memory*** (PM), together with a database of assertions, called the ***Working Memory*** (WM). Each rule consists of ***pattern elements***, called the ***left-hand side*** (LHS) of the rule, and one or more actions called the ***right-hand side*** (RHS). The RHS specifies information that is to be added to (asserted) or removed from WM when the LHS successfully matches against the contents of WM.

An English language equivalent of an *ACE* production rule is presented in Figure 2.

In operation, the production system repeatedly executes the following cycle of operations:

1. *Match*: For each rule, determine whether the LHS matches the current environment of WM.

2. *Select*: Choose exactly one of the matching rules according to some predefined criterion.

3. *Act*: Add to, or delete from, WM all assertions specified in the RHS of the

Figure 2: An Example *ACE* Production

IF a range of pairs in a cable have generated
a large number of customer reports
ANDIF
a majority of the work on those pairs was
done in the terminal block

THEN
look for a common address for those repairs.

----

selected rule.

During the selection phase of production system execution, an interpreter provides ***conflict resolution strategies*** based on the ***recency*** of matched data in WM, as well as syntactic discrimination. Rules matching data elements that were more recently inserted in WM are preferred, with ties decided in favor of rules that are more specific (i.e., have more constants) than others.

Although no structure is provided (or imposed) on PM by the general production system paradigm, the set of approximately 200 rules within *ACE*'s knowledge base can be loosely organized into subsets of related rules which collectively perform the analysis. A set of productions performs short term analysis by examining the flow of daily trouble reports. If troubles are reported for a cable that has no previous history of troubles, then information is retained that indicates that this cable may soon require attention.

When failures are reported for a cable with a history of persistent problems, *ACE* requests further detailed reports from *CRAS*, and a list of standardized procedures used to repair the types of trouble reported. This information is used to deduce:

1. whether preventive maintenance may reduce future troubles,
2. if preventive maintenance is required then what type is likely to be appropriate,
3. and, if possible, where the rehabilitation should be performed.

Thus, *ACE* not only identifies trouble spots, but also suggests how to repair them.

The main sources of knowledge for the short term analysis are:

1. textbook knowledge obtained from primers on telephone cable analysis,
2. expert advice from the developers of *CRAS*,
3. expert advice from Bell Laboratories and Bell Operating Companies' cable analysis theoreticians,

4. knowledge from local analysts within the Bell Operating Companies who use *CRAS* and perform day-to-day analyses.

Another portion of *ACE* PM contains a set of productions which know how to communicate with *CRAS*. Based on requests for more data generated by other analyses, these productions assemble the appropriate *CRAS* commands and parameters and then monitor the resulting data stream retrieved from *CRAS*.

Finally, a set of rules assemble the appropriate messages created by the system about the day's events, and call on an electronic mail facility to deliver them to appropriate users. *ACE* knows the target of each message based on the relative importance of the message to the user.

The Future: The existence of the programs described in this paper prove that the technology necessary to develop knowledge-based expert systems for maintenance applications is available today. Well understood "mature" expert system development techniques are most appropriate in the development of MESs.

The advantages of MESs are many. They allow the dissemination of knowledge (including "black art" aspects, rules of thumb, etc.) from the best (vis-a-vis highest cost) experts, in limitied supply, to lower caliber repair personnel with less expertise. Inherent in such an approach, is also the solution to repair manual update control. An expert system computer-based repair system solves the problem of out-of-date documentation hindering the effectiveness of repair personnel. Such systems also allow the capability to capture feedback and perform statistical calculations to flag problems which occur with the greatest frequency. Such data can be used to improve repair techniques or to change manufacturing or operating procedures in order to lower occurrences of the highest frequency failures.

MESs will produce the highest leverage for high capital cost, complex equipment where downtime is expensive or intolerable, for example:

- Aircraft
- Automobiles
- Buses
- Computers
- Machine Tools
- Ships
- Test Equipment
- Trains
- Weapons Systems

As an example, aircraft maintenance is currently performed, for the most part, by highly paid union mechanics. In recent years airline labor unrest has been on the rise in an environment of declining profits. Expert system technology offers a paradigm to perform maintenance in a radically improved way. Instead of a reactive approach to a long-standing structural problem in the airline industry, management now has an opportunity to solve a persistent problem.

The military is also interested in MESs for aircraft in order to decrease the time that aircraft spend on the ground. DoD has issued an RFP for aircraft MESs. The initial work, once a contract is awarded, will focus on ground based expert systems. Over time the developed systems will be transitioned into the aircraft itself, so that diagnosis can be performed in flight.

MESs are ideal for military customers due to the, for all practical purposes, infinite cost of downtime associated with weapons systems. The military acutely feels the problem of having to maintain a large pool of qualified repair technicians for specific items, despite the tenuous caliber of the personnel, the high cost associated with training these personnel, and the complexity of weapons systems. This problem is exacerbated by rapid job turnover.

Based on the fact that there is a large market for improved repair procedures to minimize downtime of complex equipment and well understood AI technology exists which can bring about the desired improvements in efficiency, the authors predict rapid growth of expert repair systems in both military and commercial applications. In summary, Maintenance Expert Systems are practical now.

Acknowledgements

The authors wish to acknowledge the assistance of Pandora Setian for preparation and editing of the manuscript which substantially improved its final presentation.

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