# A Knowledge-Based Electrical Diagnostic System for Mining Machine Maintenance

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*Abstract*—**Studies indicate that a significant portion of all mining machine failures are associated with electrical system problems. As more highly automated machines are developed, the complexity of a machine's electrical control system can be expected to increase considerably, requiring a greater degree of skill and experience on the part of mine maintenance personnel. Knowledge-based expert diagnostic systems can provide a powerful method of improving equipment maintenance by quickly diagnosing control circuit malfunctions and recommending appropriate repair procedures. To investigate the applicability of expert systems in the area of control circuit diagnostics, the Bureau of Mines has developed a knowledge-based system to diagnose component malfunctions in the electrical control circuit of a continuous mining machine. The system leads the user through the appropriate procedures required to quickly identify the faulty control circuit component. Graphical displays are incorporated within the system to assist the user in locating the various components and test points. Once the faulty component has been isolated, the system is capable of accessing a database which can provide mine personnel with information concerning specific component part numbers and the availability and location of spare parts. The expert system development tool used to build the system, the structure and development of the knowledge base, and the software used to implement the graphical displays and equipment database, is discussed.**

## Introduction

DELAYS associated with equipment failures have long been recognized as a major cause of lost production in the coal mining industry. With the recent introduction of advanced automation technology to many mining operations, mining machines are becoming ever more complex, and mine maintenance personnel often lack the specialized skills and experience necessary to diagnose and repair problems associated with the rather sophisticated control systems which are becoming increasingly common in today's mining equipment. As a consequence of this increased machine complexity, delays may increase unless significant efforts are made to make mining equipment more reliable and easier to repair.

Currently available machine-mounted diagnostic equipment such as digital readouts and indicating lights provide valuable information which greatly simplifies the diagnosis of many machine malfunctions. Yet in itself, this diagnostic information is often not sufficient to pinpoint the underlying cause of a malfunction, or to determine the proper repair action to be taken. It is the skill and experience of the mine mechanic, having a thorough understanding of the machine's basic functions and operations, that permits the pertinent diagnostic information to be properly interpreted and analyzed, and which ultimately results in the isolation of a machine malfunction to a specific machine component.

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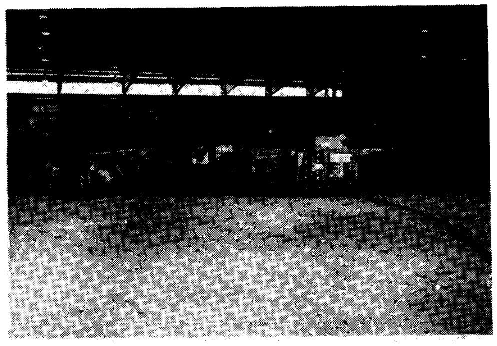

Fig. 1. Modified Joy 16CM continuous mining machine.

In recent years, a form of Artificial Intelligence (AI) known as expert systems has emerged from the universities and research laboratories, which shows great potential in solving a wide range of practical problems normally considered to require human intelligence. An expert system is a computer program which attempts to emulate human expertise in a limited problem domain. The Bureau of Mines is presently investigating the areas in which expert systems can best be applied in the mining industry to increase both safety and productivity in a cost-effective manner. The remainder of this report describes a prototype expert system developed by the Bureau to assist maintenance personnel in effectively isolating the cause of a malfunction in the electrical system of a continuous mining machine.

## Machine Description

The electrical diagnostic system developed in this study was designed specifically for the modified by Joy model 16CM continuous mining machine[1] shown in Fig. 1. Although similar diagnostic systems could be developed for practically any piece of mining machinery, the 16CM miner was chosen for this particular study due to its availability as a testbed for the performance of a number of automation-related experiments at the Bureau's Pittsburgh Research Center. The machine has been equipped with a control computer and related peripheral hardware designed to ultimately permit

[1] Use of company names is for information only and does not imply endorsement by the Bureau of Mines.

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autonomous operation of the mining machine in the absence of a human operator. The electrical control circuit has been substantially modified to accommodate the additional circuitry required to interface the control computer with the original control system components. A number of indicating lights and other diagnostic devices have been added to facilitate troubleshooting in both the manual and automatic (computer-controlled) modes of operation.

## Design Criteria

A report prepared by Woodward Associates, Inc., under a U.S. Department of Energy contract, indicates that approximately 20% of all continuous mining machine failures are caused by problems associated with the electrical system [1]. The electrical system can be categorized into three distinct problem areas: trailing cables, motors, and control system components. Because control circuit diagnostics rely heavily on human knowledge and experience, the expert system was developed to focus primarily on the diagnosis of control circuit malfunctions.

One of the main components of an expert system is the knowledge base. The knowledge base is the repository of human knowledge that the expert system needs in order to solve a problem within a particular domain. For an expert system to effectively model the expertise of an expert human troubleshooter, it is first necessary to identify the various aspects of the expert's knowledge and procedures that enable some mechanics to diagnose and repair problems more quickly and efficiently than others. The expert system must then be designed to convey the appropriate knowledge to the user in the most effective manner. In the domain of electrical control circuit diagnostics, some of the factors which characterize efficient mine mechanics can be summarized as follows.

1) Some mechanics simply have a better understanding of the fundamental structure and behavior of a machine's electrical control system. A competent mechanic is thus able to initiate a logical diagnostic procedure based primarily on first principles rather than past successful strategies or empirical associations.
2) A competent mechanic is familiar with the physical location of the various control circuit components within the machine. Practically all control circuit components are located within a number of explosion-proof enclosures, and component layout drawings may not be readily available to the underground mechanic. Inexperienced mechanics often spend a considerable amount of time unnecessarily removing and replacing explosion-proof covers in an effort to locate specific contactors or interlocks, and even highly skilled mechanics often waste time when troubleshooting new or unfamiliar equipment simply because they are unsure of the location of specific machine components.
3) Mechanics which have access to electrical drawings and are able to follow control circuit schematic diagrams are generally more proficient in diagnosing malfunctions. However, drawings may not always be available or may be unreadable. Less skilled mechanics often find complex schematics confusing and difficult to follow.
4) Experienced maintenance personnel are often more familiar with the availability and location of replacement parts than less experienced mechanics, and are often able to replace damaged components with suitability equivalent substitutes when exact replacement parts are not readily available.

Based on these factors, the electrical diagnostic expert system was designed and developed in accordance with the following criteria.

1) The expert system should lead the user through a logical diagnostic procedure by emulating the decision-making process of an expert troubleshooter.
2) The system should be capable of indicating the physical locations of specific components, test points, etc., which the user may be required to access during the course of a troubleshooting session.
3) Pertinent portions of the control system schematic diagram should be available for display.
4) Access to a database of specific component information should be available to provide information such as part numbers, quantity and location of spares, and component interchangeability data.

## Development System

Until quite recently, development of an expert system normally required special computer equipment and a trained knowledge engineer to gather the pertinent knowledge from the domain expert and then code it into a knowledge representation format using special AI programming languages. Today, however, the trend is away from systems that require specialized hardware and programming languages, and numerous development tools, often called expert system shells are commercially available which greatly reduce the effort and cost involved in building an expert system. For development of the electrical diagnostic expert system, a development tool known as LEVEL5 was chosen [2]. LEVEL5 is an inexpensive yet powerful development environment which is easy to use and which incorporates the features necessary to implement the previously established design criteria. It is designed to run on an IBM PC/XT/AT or compatible computer, with a minimum of 512K of RAM, two floppy disk drives or a hard disk, and the DOS (version 2.0 or latter) operating system. The main features of LEVEL5 are described as follows.

### *Knowledge Representation*

LEVEL5 uses a rule-based problem solving strategy, and the knowledge base is developed using a simple knowledge representation language called Production Rule Language (PRL). The knowledge base consists of a collection of IF-THEN rules which the expert system uses to solve a particular problem. Rules written in PRL consist of two parts: a condition and a conclusion. The condition and conclusion parts of each rule are made up of one or more facts, logically connected by keywords such as AND, OR, and ELSE. As the expert system is executing, it attempts to verify the status of each fact by either requesting input from the user (or external sensor), or by inferring the fact from the conclusion of another rule. When the condition set of a rule (the IF part) is true, then the rule's conclusion (the THEN part) is also true, and the facts that make up that conclusion can then be used in the condition portion of other rules. By systematically chaining through the rules of the knowledge base, the expert system ultimately comes to a particular conclusion which can be referred to as the root goal of the system, and execution of the program then terminates.

### *Inference Engine*

The inference engine is the underlying component of an expert system which defines the control strategy for searching through the rules of the knowledge base, and thus directs the reasoning process. In LEVEL5, the inference engine is an integral part of the development system, and is not tied to a particular problem or knowledge domain. The LEVEL5 inference engine permits the use of both forward-chaining and backward-chaining control strategies. A forward-chaining control strategy is a data-driven search procedure that simulates inductive reasoning. The system starts with a set of conditions, and if the facts contained in the condition set can be proven, then a conclusion follows. With a backward-chaining strategy, the system starts by assuming a particular conclusion, then works its way back through the condition set, trying to prove that the facts support that conclusion. In this way, backward-chaining simulates a deductive reasoning process. The control strategy which LEVEL5 uses during execution of an expert system is determined by the manner in which the knowledge base has been structured by the developer. Both forward-chaining and backward-chaining strategies can be implemented within the same expert system.

### *Graphics Interface*

LEVEL5 permits graphics screens to be displayed during execution of the expert system via a special PAINT command, which can be invoked from within the rules of the knowledge base. The graphics screens must be created in one of three possible formats: Telegraphic Savegraph, Dr. Halo II, or Microsoft Paintbrush Freize format. The software required to create the graphics screens is not included as part of the LEVEL5 development system.

### *Data Base Access*

A knowledge base can directly access data base files created with either dBase II or dBase III. Data base information can be passed between the knowledge base and the data base files using a set of PRL commands. These special commands provide the ability to search for and display data base information, and to append or delete data base records directly from the rules of the knowledge base.

### *Additional Features*

PRL contains a number of built-in mathematical functions, and also allows external programs to be activated directly by a knowledge base. The ability to call external programs written in any high level conventional programming language permits an expert system to do sophisticated algorithmic processing beyond the capabilities of the PRL language. LEVEL5 also supports the assignment of confidence factors for each condition and conclusion, and a report facility is available to explain the expert system's line of reasoning both during and after execution.

## Knowledge Base Development and Execution

Rule-based expert systems which contain a large number of rules can be difficult to develop and maintain. It is, therefore, advantageous to break large applications into small sections so that each section can be developed and tested individually. The electrical system of the Joy 16CM miner can be divided into four separate functional circuits: the pump circuit, the conveyor circuit, the tramming circuit, and the cutter circuit. To simplify development, a separate knowledge base was constructed for each of these four circuits. When the expert system is first started, it requests the user to specify which of these four circuits appears to be malfunctioning. Based on this input, control of the expert system is transferred to the appropriate knowledge base via the PRL command CHAIN.

Once the control has been directed to the proper knowledge base, the user is requested to supply additional information about the specific nature of the problem (e.g., machine will not tram, machine will not tram in reverse, etc.) and the mode in which the machine is being operated (e.g., from machine, remote box, or on-board computer). The user supplies this information by answering a series of simple true-false or multiple-choice questions. Given this information, the expert system begins to lead the user through a diagnostic procedure designed to quickly identify the cause of the problem.

## Diagnostic Approach

The diagnostic approach used in the development of the knowledge base is based on a method of decision tree analysis. Using information derived from the equipment maintenance manual [3] and electrical drawings, and through observation of the procedures used by efficient mine mechanics, a decision tree can be developed to mimic the way a human expert makes decisions and arrives at conclusions. The decision tree is then translated directly into the IF-THEN rules which make up the expert system's knowledge base. The manner in which a decision tree can be translated into PRL rules is illustrated in Fig. 2, which shows a small portion of a decision tree developed to diagnose a faulty pump starting switch and the corresponding rules written in PRL.

Whenever the expert system is attempting to prove a particular conclusion, the inference engine searches through the rules and facts in the exact order in which they appear in the knowledge base[2]. By properly ordering the rules and facts, the knowledge base developer can control the exact sequence through which the expert system proceeds to solve a problem. This assures that the diagnostic procedure will follow the decision-making process of an efficient human troubleshooter. Procedures which require the removal of explosion-proof covers are performed only after all pertinent external switch settings and diagnostic readout information has been checked,

[2] If confidence factors are used, LEVEL5 will pursue those rules which can achieve the highest degree of confidence first.

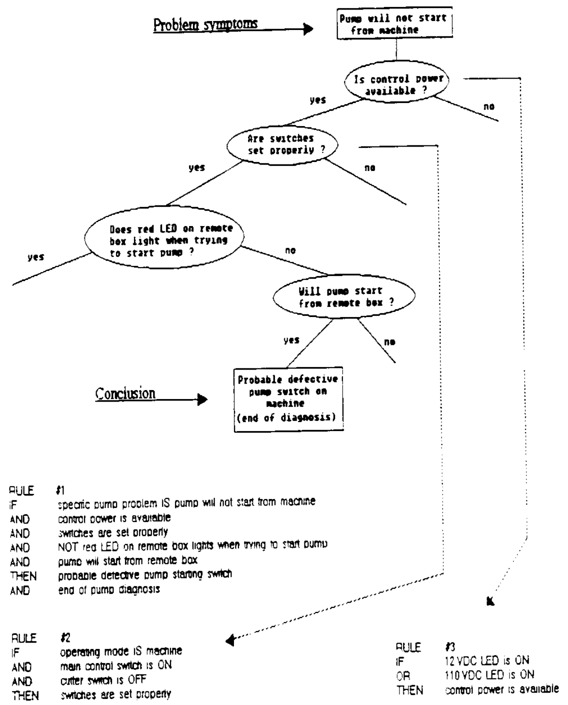


Fig. 2. Partial decision tree diagram and corresponding PRL rules.

and the problem area has been sufficiently isolated to minimize the need to access electrical enclosures.

## Customized Displays

LEVEL5 normally uses a predefined default format to display requests for user input or to present its conclusions. Facilities are available, however, which permit the developer to customize the format in which these screens are presented to the user. In the electrical diagnostic expert system, customized displays were developed to graphically indicate the physical location of the various test points, switches, and other electrical components which the user is required to access during the session. These displays can be created using LEVEL5 ASCII text editor, which supports the use of the ASCII graphics characters. To facilitate the design of customized screens for this application, the line-draw and macro features of a commercially available word processing program were utilized. One such customized screen is shown in Fig. 3.

## Schematic Diagrams

Once the expert system has arrived at a conclusion and the appropriate conclusion display has been presented, a small portion of the electrical schematic diagram is displayed. To avoid confusion, only that portion of the schematic which is pertinent to the immediate problem is displayed, and the suspected faulty component is highlighted. These displays were created with Microsoft Paintbrush, a commercially-available graphics program, and are called to the screen from within the rules of the knowledge base using the PRL command PAINT. Fig. 4 shows the portion of the schematic diagram which would be displayed in the diagnosis of a defective pump start switch.

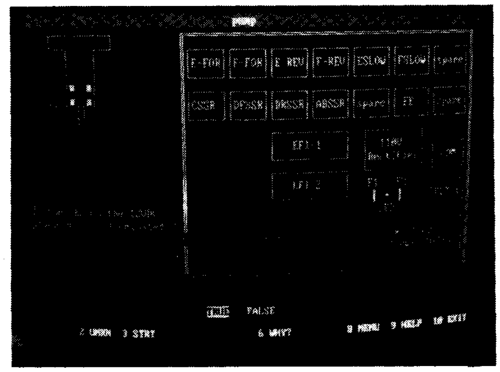


Fig. 3. Customized display requesting information from user.

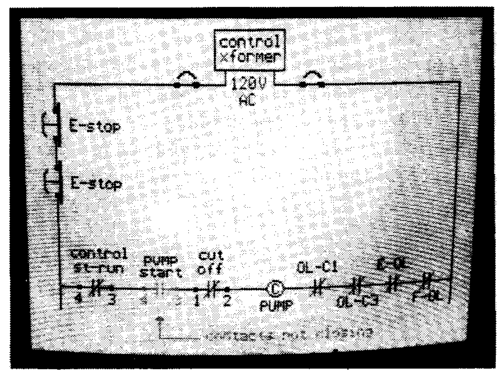


Fig. 4. Schematic display for defective pump start switch.

## Data Base Information

After viewing the schematic diagram, the user may be asked whether additional information about the identified faulty component is required. If so, the system proceeds to search through a data base which contains specific information on each component in the machine's control circuit. The component's manufacturer, part number, availability and location of spare parts, and other pertinent information are then presented. The component data base was created using dBase III Plus, a relational database program available from Ashton-Tate. Access to the data base is provided from within the rules of the knowledge base using a special set of PRL commands.

## User Interface

The electrical diagnostic expert system is currently designed to interact with the user via a standard IBM-compatible computer with a conventional keyboard and display unit. Although this might be acceptable for use in surface repair or training facilities, it may not provide a practical or desirable interface for use by underground mine mechanics in a working section of a mine. The Bureau of Mines is currently investigating methods which would enable the practical use of such diagnostic expert systems in the underground areas of a mine. Custom-designed hardware, touch screens, and voice recognition systems are presently being considered. In addition, sensor-based expert systems that would minimize the amount of human interaction required during the diagnostic process are currently under development. For underground use, it is of utmost importance that the computer hardware be compatible with the mine environment. Hardware must be designed to withstand dust, moisture, and machine vibration. The hardware must also meet intrinsic safety requirements.

## Conclusion

The Bureau of Mines has developed a prototype expert system to diagnose problems in the electrical control circuit of a continuous mining machine. The system was developed using LEVEL5, a simple rule-based expert system building tool, and is designed to mimic the decision-making process of an efficient mine mechanic. Custom-designed screen displays and data base access have been incorporated to facilitate interaction with the user and expedite equipment repairs.

Easy to use development tools are now available that can enable mine personnel to build diagnostic expert systems without the need for extensive computer training and experience. Using conventional computer equipment, diagnostic expert systems can now be used by mechanics in surface repair facilities, or to assist in the training of apprentice mine mechanics. For use in the underground areas of mine, a more practical hardware configuration and user interface will be required.

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He joined E.I. Du Pont DeNemours and Company, Victoria, TX, as an Engineer in the Acids Mechanical Division, Polymer Intermediates Department, where he was involved in the installation and maintenance of industrial process control systems. In 1974 he joined the Barnes and Tucker Company as Electrical Engineer and advanced to the position of Electrical Superintendent, where he was involved in the installation, operation, and maintenance of the power distribution systems and industrial control systems. In 1986 he joined the U.S. Bureau of Mines as Electrical Engineer, where he was involved in the development of expert systems for mining machine maintenance until his death in January 1989.

Mr. Berzonsky was a member of the Mining Electro-Mechanical Maintenance Association and the IEEE Industry Applications Society, Power Engineering Society, and Engineering Management Society.