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An on-board diagnostic system for the South African mining industry*

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SYNOPSIS

This paper sketches an expert system for use underground in pinpointing problem areas in the operation of machines.

The system is typically a software 'shell' designed to accommodate a series of 'if-then' rules that are interlinked to systematically search for the cause of the problem. During the search, the system asks a series of questions that have to be answered by the operator and then, when necessary, by an artisan. The rules of the system are generated by a knowledge engineer whose function it is to gather the necessary diagnostic information and prepare it in the required format for the expert system.

Much still requires to be done in the development of such systems and in the testing of hardware to withstand the mining environment.

SAMEVATTING

Hierdie referaat skets 'n ekspertstelsel vir ondergrondse gebruik om die probleemgebiede in die werking van masjiene noukeurig uit te wys.

Tipies van die stelsel is 'n 'programmatuurdop' wat bedoel is om 'n reeks as-dan-reëls te akkommodeer wat onderling verbind is met 'n sistematiese soektog na die oorsaak van die probleem. Tydens die soektog vra die stelsel 'n reeks vrae wat deur 'n operateur en, indien nodig, dan deur 'n ambagsman beantwoord moet word. Die reëls van die stelsel word ontwikkel deur 'n kennisingenieur wie se taak dit is om die nodige diagnostiese inligting in te win en dit in die vereiste formaat vir die ekspertstelsel voor te berei.

Daar moet nog baie werk gedoen word in verband met die ontwikkeling van sodanige stelsels en die toets van apparatuur wat teen die mynomgewing bestand is.

Introduction

The recent mechanization of various operations within sectors of the South African underground mining industry has once again highlighted the growing shortage of suitably trained artisans in the industry.

This shortage, which is a prime contributor to low availabilities and high maintenance costs, is likely to worsen, and it is therefore essential to identify ways and means of increasing availabilities and lowering costs with the manpower that is available at present.

One solution is to use an on-board diagnostic system on mining machines to reduce the time taken and the level of skills required to troubleshoot faults on the machines. In its most advanced form, the system would use a computer to monitor the machine-operating conditions, diagnose faults, and display relevant information and recommendations to the operator, serviceman, and artisan.

Although simple in concept, such systems have several problems associated with their practical implementation, and it is essential that these problems should be addressed during each stage of development. The final system must, above all, be effective, easy to use, and durable while operating in a very harsh environment.

This paper examines the development of such a system.

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Definition of a Diagnostic System

A diagnostic system is essentially an aid to pinpointing problem areas in the operation of a machine. Before the advent of computers, diagnostic systems were, and still are to a large extent, charts supplied by equipment manufacturers indicating the probable causes of a range of sub-standard operating conditions. These charts are typically included in maintenance and service manuals, but are also supplied as large wall-hangings for workshop use.

With time, machines have become increasingly complex and sophisticated, and the number of charts required to be carried by the artisan, coupled with the problem of legibility in a dark and often dirty location, has led to their minimal use in a breakdown situation.

A further limitation of diagnostic charts is that they cannot take into account the specific environment and circumstances in which a machine is working, and they seldom, if ever, are updated by local experience.

The knowledge, experience, and troubleshooting capabilities of the artisan are therefore all important, and this is where the problem often occurs since there are too few artisans in the industry with the necessary skills and experience.

It is clear that the speed with which a breakdown is fixed is determined by

(a) the operator's recognizing the problem at an early stage;
(b) the operator's calling out the correct artisan;
(c) the artisan's having the correct knowledge and experience; and
(d) the artisan's having and using the correct tools and

spares to effect the repair.

Each of the above is a problem area in its own right but, to be of real value, any solution must address the whole set of problems.

In theory, the solution would lie in fitting to each machine a diagnostic aid that would warn the operator of a problem or impending problem, recommend which type of artisan should fix it, and then recommend to the artisan the correct procedure, tools, and spares for the repair.

With the advent of very powerful microprocessors and high-capacity solid-state memories, and the increasing versatility of software, collectively known as 'expert systems', it is theoretically possible to design such an on-board computer-based diagnostic system. The system would, in effect, replicate the diagnostic charts and utilize the knowledge of relevant experts to systematically pinpoint faults using the monitored conditions of the machine as a starting point; and would then recommend corrective action.

In practice, however, much of this still involves leading-edge technology, and any attempt to introduce such a comprehensive system directly into the harsh underground environment would almost inevitably lead to failure. For this reason, it is necessary to set realistic, achievable targets, and then learn from the practical performance of each stage.

The Systematic Development of a Diagnostic System

A diagnostic system can be perfectly useable and effective without being hardwired to probes on a machine and, since the technology is still being developed, it makes good sense to start with a simple system from which more powerful and comprehensive systems can later be developed.

Two levels of system have been identified, each of which could be developed in stages as the necessary software and hardware become available, and operating experience is gained:

Level 1 Stage 1 Designed for the breakdown situation, this is an expert system that will assist the operator and artisan in quickly locating a fault condition. The system is in a computer housed on the equipment, but not wired to probes on the equipment.

Level 1 Stage 2 The stage 1 system has been upgraded to include repair procedures and lists of the required tools and spares.

Level 1 Stage 3 This is a machine-interactive stage 2 system, with condition-monitoring probes hard-wired to the on-board computer.

Level 2 Stage 1 Specifically for the maintenance situation, this is a non-interactive expert system and database designed to operate from a fixed computer installation in the workshop. It will assist the artisan in quickly locating a fault, or sub-standard condition, and will also recommend repair procedures and list the required tools and spares. This would be useable with different types of machines.

Level 2 Stage 2 This is a stage 1 system upgraded to receive information from the equipment probes via flexible leads.

Objectives for the Level 1 System

The objectives for the level 1 system have specifically been formulated to take account of the hard-rock underground mining situation, and are summarized below.

(a) The environment is harsh, with high temperatures, humidity, and acidity, and the presence of grease and oils.
(b) Operators and servicemen have limited skills in recognizing and diagnosing faults, and do not necessarily read well.
(c) On a three-shift operation, there is a 67 per cent chance that the units will break down when the artisan labour underground is limited.
(d) Machines are often situated a considerable distance from the workshop, and the operators are not in constant communication with the maintenance personnel.
(e) It can take several hours between a call-out and the arrival at the machine of the artisan and his aide. Should they have either no spares or the wrong spares, it will take considerably longer to rectify the problem.
(f) In most cases, the artisans are fitters, electricians, or boilermakers, and they cannot do one another's work.
(g) In the case of a complete failure at or near the face, the only lighting available will be from cap lamps.

Taking cognizance of the above, the objectives for the level 1 and higher-level systems are as follows.

(1) The hardware and its packaging must be able to withstand the environment.
(2) The computer screen must be selflit, legible, wipeable, and unbreakable.
(3) The keyboard must have as few keys as possible, be wipeable (of the sealed pressure-sensitive type), and be unbreakable.
(4) The expert system must ask for and deliver clear, unambiguous information and, as a minimum requirement, must advise the operator when it is necessary to call out an artisan, and the type of artisan required.
(5) The software must be 'user friendly', and operator/artisan input should be minimal ('Yes' and 'No', or 'multiple choice' keys).
(6) The 'dialogue' with the computer should be stored and communicable to the surface, either by the use of a removable-bubble memory type of cartridge, or by the carrying of the computer to the nearest telephone where a modem can be utilized.

The last objective is important to ensure that the artisan has the maximum amount of information at his disposal before he goes down the mine, so that he can gauge the nature of the fault and take the appropriate tools and spares with him.

The Expert System

An expert system in the context of this paper is a computer program that can aid in the diagnosis of a machine fault using information supplied to it on the symptoms of the fault, e.g. low oil pressure, zero voltage, etc.

The expert system is typically a software shell designed to accommodate a series of 'if–then' rules that are interlinked to systematically search for the cause of a problem. During this search, particularly in the level 1 to level 3 cases, the expert system will ask a series of questions that will have to be answered by the operator in the first instance and then, when necessary, by the artisan.

To obviate the necessity for a conventional keyboard on the machine, the program will ask the operator/artisan questions requiring a simple 'Yes' or 'No' answer; for example, 'Is there fuel in the tank?' or 'Is the voltage at the alternator terminals less than 20 volts?'

The rules of the expert system are generated by a knowledge engineer, whose function it is to gather the necessary diagnostic information, be it from manuals, charts, or experts in the field, and to prepare it in the required format for the expert system. The knowledge engineer is crucial to the success of any computer-based diagnostic system, since his interpretation and preparation of the information determine the usefulness of the final system.

Expert systems can quickly become complex, and a fairly comprehensive diagnostic system for a load–haul–dump truck, for example, would require the inclusion of several hundred rules. In order to handle such large amounts of information and produce answers in a reasonable time, the expert-system shell must be very fast and, by implication, highly efficient.

In the level 1 case, the expert system is specifically designed to rectify breakdowns, and therefore does not require rules to identify the cause of the malfunctions that would normally be fixed during a major service, e.g. excessive smoke emission. These rules are required in the level 2 system.

Computer Hardware

The quality of the computer hardware is as critical as the quality of the software, particularly in view of the harsh operating environment. From the point of view of software processing, the computer must have a very fast processor and/or co-processor, and a large amount of random access memory. Since most mining equipment is subject to vibration, the use of floppy disks and hard drives should be avoided. Programs and data should be stored in non-volatile memory.

With regard to the structural integrity of the hardware, it is necessary for the screen to be flat and covered by a tough synthetic sheet, e.g. Lexan, and for the display to be readable in the dark. In view of the highly erosive and corrosive environment, the hardware must be completely encased in a protective sheath and mounted in a case with anti-vibration mountings. The keyboard, which should have a maximum of 6 keys, must be rugged, waterproof, and oilproof and, ideally, should be covered by a suitable membrane.

In view of the environmental conditions, the hardware should ideally meet military specifications, but at the very least must be tailormade for the mining environment.

Merging of a Database and an Expert System

In the level 2 case, which is a workshop-based diagnostic system, there is an obvious advantage to be gained from storage in the computer of the information required to effect the repair.

It is beneficial, for example, to store illustrative pages of a workshop manual that can be displayed on the screen when required. The display of the tools and spares required, by description and part number, is a further enhancement, as is a statement as to whether or not the tools and spares are available.

To achieve this in practice, a large-capacity database is required capable of storing such information for all the machines being maintained in the workshop. Fortunately, even at personal-computer level, this is fast becoming a reality.

The level 2 system would typically have a single database in the workshop linked to peripheral computers at stations easily accessible to the artisans working on the machines. Ultimately, the workshop database would be linked to the main store's database so that the availability and, where necessary, the location of the desired spares could be ascertained.

Linking of Monitoring Probes to the Expert System

As experience with expert systems is gained and their practicality proved, it will become feasible to directly link condition-monitoring probes or sensors on the machine to the computer in order to speed up the diagnosis.

This is straightforward in concept, but there are pitfalls in practice. At present each probe requires at least 2 wires and, with say 30 probes on the machine, the number of wires and thus the potential for faults in the wiring become significant.

To comprehensively monitor the condition of the machine from bumper to bumper, many more probes will be required, and the complexity and likelihood of broken wires and faulty probes will probably outweigh the advantages.

A serial bus wiring system is currently being developed to alleviate this problem. This will allow groups of probes to be connected in parallel to one set of wires, the signals from these probes being encoded and transmitted in sequence to the computer. Such a system will dramatically reduce the extent of hard wiring, although it will probably result in a significant increase in overall cost.

A simpler and cheaper short-term solution is to provide LED (light-emitting diode) displays at the required probes to indicate whether or not the measured condition is within specification, and whether or not the probe is faulty. This will then enable the operator to visually check the status of each measuring point and supply such information to the expert system. The required technology is available, and will enable the level 1 stage 2 system to be upgraded to stage 3, and the level 2 stage 1 system to stage 2 fairly simply.

Compiling the Expert System

Expert systems can either be developed using a commercially available shell or can be specially written to suit a specific requirement. In the initial development of a diagnostic system, it is easier to use a commercial shell and, since the diagnostic logic remains the same, it can always be used in a custom-built program at a later stage. In either case, speed of program execution is important in order to minimize the response time.

However, the key to an effective diagnostic system is not the program, but its diagnostic logic, which is entered in the form of rules. This, as previously mentioned, is the domain of the knowledge engineer, who needs a good understanding of how the program operates and the input formats required, as well as a thorough understanding of the operation of the mining machines under consideration. He does not need to know in detail how the various components of the machines work, but he must know enough to ask experts the right questions, and to search out additional information from other sources.

Using the gathered information, the knowledge engineer typically compiles 'process forests', which are essentially maps of sequential processes or dependencies from which 'if–then' rules are formulated. A section of a process forest is shown in Fig. 1, and the rules derived from it in Fig. 2. The experts consulted must agree on the logic contained in the process forests in order to ensure that the generated rules are based on valid assumptions.

A powerful feature of expert-system shells is that they will accept these rules in any order, and then forward or backward chain through the rules, asking for further information only when necessary, until a solution or probable solution is found. Forward chaining starts with the facts (symptoms) and tries to work towards a goal (the cause of the fault condition), while backward chaining starts with a goal (one of many possible causes) and looks for the supporting evidence to satisfy that goal. The program continues to search through the goals until the supporting evidence matches.

Rule Number 12

If:

The problem with the engine is starting difficulty

and

the difficulty is that the starter does not turn the engine

and

with the vehicle in neutral, the park brake on, and the ignition key switched on, an attempt to start the engine causes the ignition light to glow brightly

and

when the key is turned, the solenoid makes a 'clicking' sound

Then:

(1) A problem exists in the heavy-current lead from the battery to the solenoid (probability 90/100).

(2) The solenoid is faulty—replace with a new one (probability 80/100).

(3) The starter is faulty—replace with a good one (probability 50/100).

Fig. 2—An example of a rule in an expert system

A simple example gives some idea of the procedure followed by the knowledge engineer when generating an expert system.

Symptom of the fault—'The engine won't start'.

The cause of the engine's not starting can be electrical, pneumatic, hydraulic, or mechanical, depending on the configuration of the starting circuit. The problem can lie in the starting circuit, the engine, the torque converter/

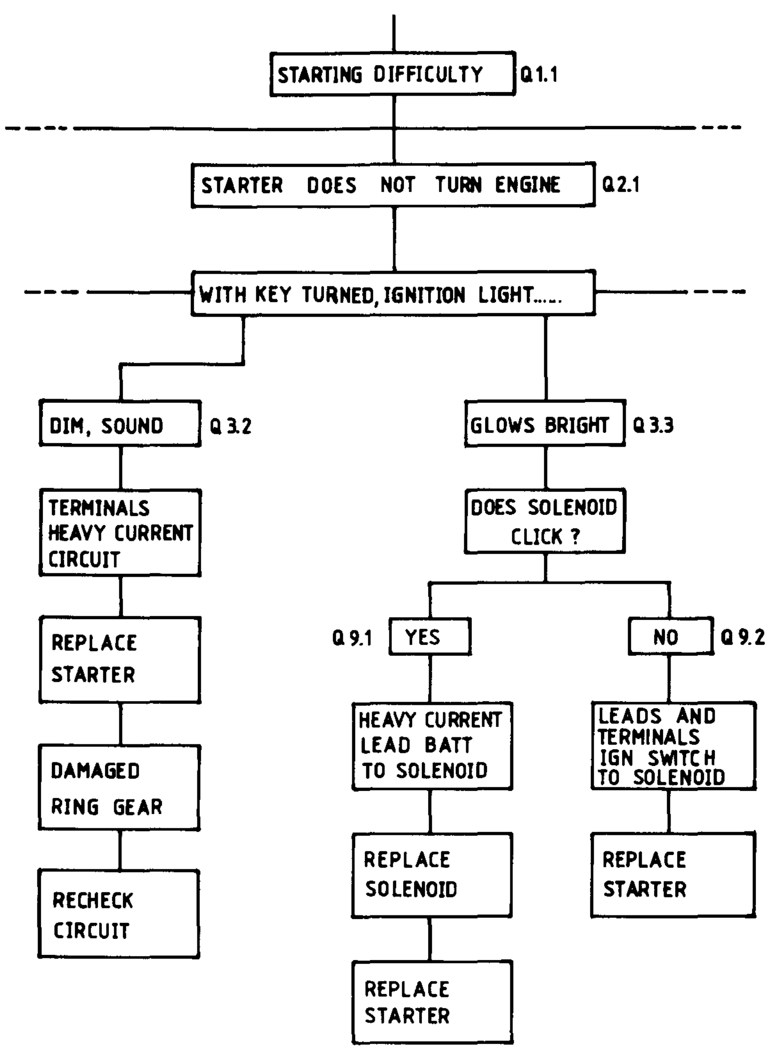

Fig. 1—Section of a process forest

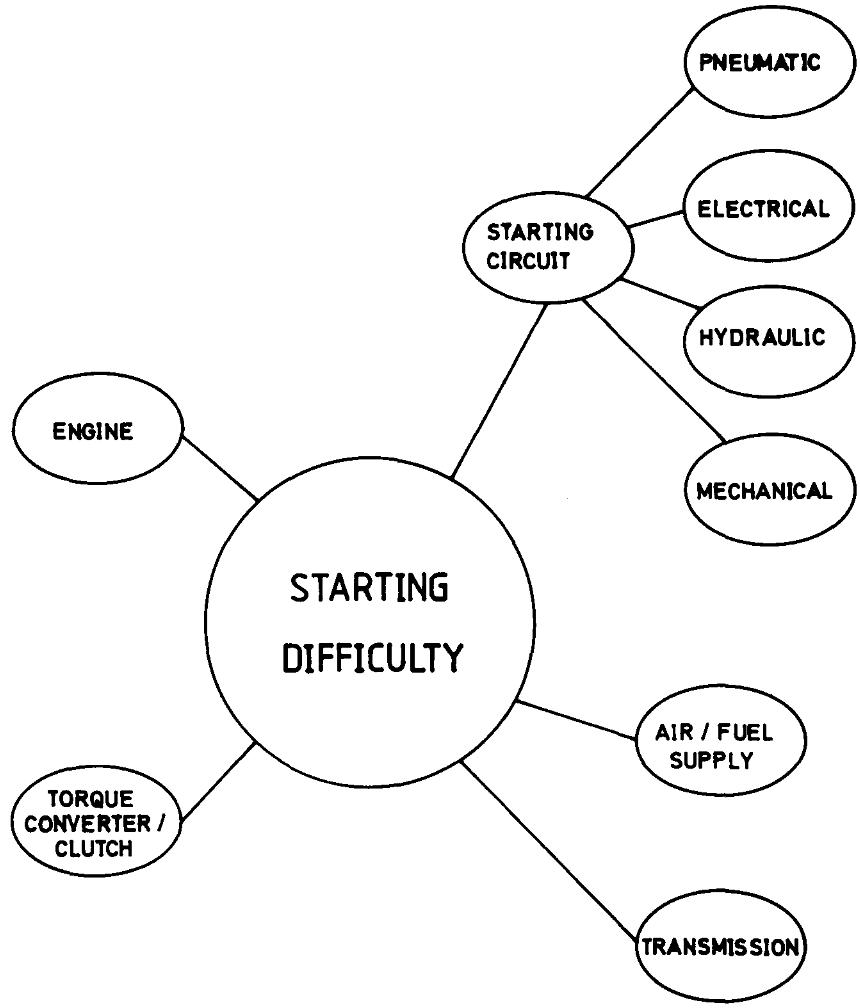

Fig. 3—A system map (or concept graph)

clutch, or transmission.

Each of these possibilities must be addressed as an entity in order to produce a logical string of 'if–then' rules for the expert system covering all possible causes of failure.

It helps to map these major system circuits or components in which the fault can occur, as shown in Fig. 3, in order to generate the process forests in an orderly sequence. This also assists the knowledge engineer in formulating questions to the expert in a logical order.

It is not practical to give a detailed example of rule generation in this paper, since to locate, for example, a starting fault requires the generation of many rules.

The symptom 'starter does not turn engine' requires the generation of 32 rules for the fault to be correctly diagnosed. 'Starter turns, but engine does not start' requires 41 rules, and so on. The generation of a complete set of rules for the diagnosis of all engine-related faults is therefore a lengthy and painstaking process but, once the expert system is running and 'debugged', the potential savings in machine downtime are enormous.

Conclusion

The diagnosis of machine faults using expert systems in on-board computers is still under development. The collection and preparation of the knowledge required by the systems are time-consuming processes, and a complete system covering the engine, drive train, steering, brakes, hydraulics, etc. can require many hundreds of rules.

In view of this, it is inevitable that machine-diagnostic systems will be developed in stages, and it is likely that these systems will first become available as modules, e.g. an engine module, a transmission module, etc. These modules will be linked at a later stage to collectively form a complete machine system.

There is also much work still to be carried out on the development and testing of hardware capable of withstanding the mining environment, and suitable serial bus systems are still in their infancy.

Nonetheless, the potential rewards significantly outweigh the problems, and it is expected that, in the not-too-distant future, many of the machine types at present operating underground and on surface will be equipped with their own diagnostic systems, which will contribute significantly to reduced downtime.

Engineering awards*

One of the most serious national challenges facing South Africa today is the balancing of the mismatch between education and employability.

Speaking at the annual G.R. Bozzoli Award Presentations held at the University of the Witwatersrand recently, Dr A.M. Rosholt, Chancellor of the University, said that, unless a complete restructuring of the education system was undertaken by the government, the problem would not be solved and there would continue to be an oversupply of unskilled and semi-skilled workers and too few skilled.

'The business sector must continue to support education, particularly tertiary, but needs to be more specific in its requirements from the system,' said Dr Rosholt. 'Once these requirements have been set out, it is the responsibility of the universities to meet the needs of the business sector.'

Dr Rosholt's speech preceded the presentation of the G.R. Bozzoli awards in recognition of outstanding services to engineering education. These awards, presented by the Faculty of Engineering, were introduced in 1987 and take the form of bronze plaques.

This year there were three recipients of the award—AECI, Mr Edward Pavitt, and the South African Institute for Steel Construction.

Accepting the award for AECI, Executive Director Mr Dries Nieuwoudt said: 'Our company is proud to be one of the recipients of this prestigious award. The AECI Group places high priority on the promotion of quality and extent of engineering education in South Africa. Much of our interest has been focused on the University of the Witwatersrand as one of the leading engineering education institutions in the country.'

Mr Pavitt, one of the few individual recipients of the award since its inception, has been involved in engineering since graduating from Wits in 1940. Since then his career has followed an exemplary path culminating in seats on some 39 quoted companies. During his period as Chairman of Gencor, Mr Pavitt was instrumental in arranging the financial package that allowed for the construction of the new Chamber of Mines Engineering Building at Wits.

The third G.R. Bozzoli Award for 1989 was presented to the South African Institute of Steel Construction, for its continuing support of engineering education. Mr Kurt Horngren accepted the award with the announcement that the Institute would be sponsoring 15 new civil-engineering bursaries each year from 1990.

* Press release from Lynne Hancock Communications, P.O. Box 1564, Parklands, 2121 South Africa.

Left to right: Professor D. Glasser (Dean of the Faculty of Engineering, Wits), Mr K. Horngren (Director of the SA Institute of Steel Construction), Mr D. Nieuwoudt (Executive Director of AECI), Mr T. Pavitt (former Chairman of Gencor), and Dr A.M. Rosholt (Chancellor of Wits)