Chapter Three
Emerging Technologies for Maintenance Job Aids

3.0 INTRODUCTION

Maintenance is fast becoming one of the most frequent application areas for job aiding. Maintenance job aids range from automatic preventive maintenance schedulers, to systems that monitor equipment status and recommend maintenance based on trends in equipment behavior, to systems that aid in fault diagnosis and repair. Application domains range from production equipment (e.g., clutch assembly machines), to process equipment (e.g., turbine generators), to high technology specialized equipment (e.g., fighter aircraft). There is a range of methodologies employed, as well, including algorithmic approaches for the preventive maintenance schedulers to expert systems for fault diagnosis and repair. The technologies employed encompass a range from VAX mini computers to desktop microcomputers linked to video disks. This chapter addresses extant approaches to job aiding in maintenance, the prospects for using emerging technologies for such systems, and the impact of emerging technologies on human performance, particularly in aviation maintenance applications. This section also calls for a new design philosophy in building job aids. A study which used this philosophy and compared three different levels of aiding on a task is also discussed. Some of the results of the study and their applicability to maintenance job aids are presented.

This chapter is similar to a previous review of job aids (see Chapter 5 of Shepherd, et al., 1991), in that many of the systems encountered were concerned with technological developments, rather than performance achievements. Whereas that previous work identified some of the difficulties with introducing advanced technology job aids into an operational environment, this discussion addresses some of the fundamental problems with past approaches to job aids and presents a design philosophy which capitalizes on the skills and abilities of the operator in order to produce a combined human-computer system that attains increased performance.

3.1 SURVEY OF MAINTENANCE JOB AIDS

A survey of academic, industrial, and popular literature revealed a wide variety of approaches to building maintenance job aids (see Appendix). These differing approaches include both hardware and methodological considerations, ranging from stand-alone, automatic scheduling systems to portable, interactive troubleshooting systems. The hardware aspects are addressed first, followed by a discussion of some of the different methods used.

3.1.1 Hardware Employed

The following systems exemplify different hardware approaches used for maintenance job aids. These systems are presented in order of increasing sophistication.

Folley and Hritz (1987) describe an expert system that assists in troubleshooting clutch assembly machines on a production line. Fault lamps above the machine stations indicate which stations are malfunctioning. A technician takes a maintenance cart to the malfunctioning station. The cart carries a two-button control and a monitor and the technician connects these to a junction box at the station. This junction box links the monitor and control to a remote computer and video disk player. The technician uses the control to move through a menu system to specify the faulty station. The computer then specifies the tests to be performed, along with graphic displays of the equipment, and the technician enters the results of the tests. In this way, the computer guides the technician through troubleshooting and repairing the malfunctioning equipment.

A similar system developed by the Electric Power Research Institute (EPRI) also uses a video disk player for displaying maintenance information and procedures for gas-turbine power plants. This system uses a dual processor computer system. One processor manages an expert system, while another controls a video disk player. The EPRI system also uses voice recognition and synthesis for input and output, respectively.

General Motors developed an expert system to assist in vibration analysis of production machinery (cf. "GM unveils `Charley'..."). Named after a retiring technician with many years of experience, `Charley' was intended to help less experienced technicians locate parts that needed repair in production equipment with rotating components. Charley stores a signature file for each properly operating piece of equipment; technicians record the vibration signature of a problematic piece of equipment with a special data recorder and then connect the recorder to a Sun workstation. Charley compares the newly recorded signature with the database and begins diagnosing the problem. Charley guides interactions, may ask the technician for additional information, and explains its troubleshooting strategies. Charley can also be used as a consultant and allow a technician to explore `what if' questions. Finally, Charley is also used to train new technicians. The emphasis of the system is on preventive maintenance, rather than repair of failed equipment.

McDonnell Douglas developed the `Avionics Integrated Maintenance Expert System' (AIMES) for use on F/A-18 fighter aircraft (cf. "McDonnell Douglas flight tests..."). AIMES is a self-contained on-board box which contains a microprocessor and records flight avionics data on a cassette for later analysis. Production rules detect and isolate avionic failures at the electronic card level. AIMES generates queries and tests based on data and concludes whether a fault is present. If there is a fault, AIMES supplies the fault data, the card name, and the reasoning that led to the fault isolation conclusion.

The telecommunications industry is a large user of advanced technology maintenance aids, particularly in network switch and cable analysis (cf. "Expert system from AT&T..."). The `Automated Cable Expertise' system runs automatically each night to detect trouble spots in cables. Upon identifying a problem, it reports the repair history of the area and suggests corrective action.

3.1.2 Methods Employed

The following systems exemplify the range of methodologies employed in maintenance job aids. These systems are presented in order of increasing sophistication.

Berthouex, Lai, and Darjatmoko (1989) discuss a system for determining daily operations for a wastewater treatment plant. This system is billed as an `expert system', although it was developed using standard spreadsheet (Lotus 1-2-3) and database software (d-Base III), rather than one of the many production system shells. (Expert systems have historically been written using production rules (if-then clauses) in one of many languages specifically designed for that purpose, for example OPS5 or LISP. Popularization of the term `expert system' has led to decreasing precision of use of it.)

`Process Diagnosis System' (PDS) was developed by the Westinghouse Research and Development Center and Carnegie Mellon University for maintenance of steam generators. PDS is a condition monitoring system for preventive maintenance in order to alleviate both breakdown maintenance and unnecessary maintenance. The system is designed to detect deterioration early and predict the duration of safe operation. PDS also recommends specific preventive maintenance for regularly scheduled down times.

Vanpelt and Ashe (1989) describe the `Plant Radiological Status' (PRS) system for nuclear power plants. The PRS system presents a three dimensional model of the power station and equipment so that maintenance teams may plan maintenance tasks in advance. The PRS system facilitates access to and interpretation of radiological conditions by identifying hotspots and contaminated areas, as well as identifying obstructions and available workspace. The goals of the PRS system are to reduce maintenance time and radiation exposure.

Several systems for supporting operations and maintenance were reviewed by Bretz (1990). One of the systems was developed by Chubu Electric Power Company and Mitsubishi Heavy Industries, Ltd. in Japan. This comprehensive expert system assists in power plant boiler failure analysis and maintenance planning. The failure diagnosis reports the most probable causes for failure, guidelines for inspection, the items to be investigated, repair methods, and suggested preventive maintenance. The maintenance planning subsystem automatically prepares daily repair schedules, a work estimation plan, and work specifications.

The distinction is sometimes made between `deep' and `shallow' knowledge in expert systems. The knowledge typically represented in production systems is considered shallow knowledge because it contains only antecedent-consequent relationships without any information as to why one thing follows from the other. Deep knowledge, on the other hand, captures the functional and causal relationships between the components of the object or system being model. Atwood, Brooks, and Radlinski (1986) call `causal models,' which use components functions as the basis for their reasoning, the next generation of expert systems. Clancy (1987) describes a system for diagnosing switch mode power supplies which uses a model of the component level of the electronics for its diagnosis. Whereas one can test for signal presence at the module level of the electronics, the component level is concerned with the way in which a signal changes as it passes through the components. Finally, a system developed for Britain's Central Electricity Governing Board uses a model of the cause and effect relationships inherent in turbine generators for diagnosis and maintenance (see "Expert system probes..."). This expert system monitors and analyzes the vibration patterns of the equipment in its analysis.

The most sophisticated system encountered in the survey is the `Testing Operations Provisioning Administration System' (TOPAS) developed by AT&T. Clancy (1987) describes TOPAS as a real-time, distributed, multi-tasking expert system for switched circuit maintenance. TOPAS performs trouble analysis, localization, and referral of network troubles. Clancy claims that TOPAS "does network maintenance without human intervention or consultation" (p. 103). If this is true, then TOPAS is not really a job aid, because it performs the job itself.

3.2 THE USE OF ARTIFICIAL INTELLIGENCE IN JOB AIDS

The methods and design philosophies used in building job performance aids vary with the designer(s). While some of the systems surveyed placed the technician in charge of the troubleshooting and maintenance, the majority of the approaches relied on artificial intelligence. The following describes various artificial intelligence approaches and their impact on human performance.

3.2.1 Expert Systems

Expert systems typically have three components: a rule base, a knowledge base, and an inference engine. The rule base contains the problem solving strategies of an expert in the domain for which the system was developed. The rule base is made up of production rules (if-then clauses). The knowledge base contains the history and the current data of the object under consideration (this object may be anything from an aircraft engine to a medical patient). The inference engine is responsible for determining what rules get activated and when the system has solved the problem or is at an impasse. Expert systems are typically written in a programming language specifically designed for such use, such as LISP or OPS5.

Typically, the human expert is not the person who builds the expert system, rather he/she interacts with a `knowledge engineer' who is responsible for extracting the expert's expertise. One difficulty with expert systems has frequently been referred to as the `knowledge engineering bottleneck'; it can be difficult to access and program the knowledge of the expert into the expert system. For instance, the expert may not even be aware of what he/she does to solve a particular problem. Furthermore, it is impossible to guarantee that the rule base contains all of the knowledge of the expert.

3.2.2 Knowledge-Based Systems

Knowledge-based systems place less emphasis on production rules as a way of representing knowledge, and more emphasis on using a large database of information. This database may consist of information such as vibration patterns of equipment, as in Charley discussed above, or it may consist of typical hardware configurations, for instance. The point of knowledge-based systems is that they rely on a large body of readily-available information for the bulk of their processing.

3.2.3 Model-Based Systems

Model-based systems are an attempt to produce more robust problem solving systems by relying on `deep' representations of a domain. The models depend on a description of the functionality and relationships of the components that make up the domain. Model-based systems are concerned with not only how a component functions, but why it functions that way. Developers of model-based systems believe that these systems will be able to solve novel problems, whereas expert systems can only solve problems with which an expert is familiar.

3.3 HUMAN PERFORMANCE IMPLICATIONS OF ARTIFICIAL INTELLIGENCE APPROACHES

The human performance implications of using an artificial intelligence-based problem solver are many. All of these systems revolve around the `machine expert' paradigm, in which the computer controls all problem-solving activities. One problem with the machine expert paradigm is that because computers do not have access to the `world', they must rely on a person to supply all relevant data about the world. Thus, the machine expert directs tests to be run and requests the results of those tests. Based on these data, the computer requests more information or reaches a conclusion, and that conclusion may be erroneous. In the words of one cognitive engineering researcher, the human is reduced to a "data gatherer and solution filter" for the machine.

One problem associated with this lack of environmental access is that the person may have knowledge that the computer does not. Since the computer directs the problem solving, it may never ask for information that may be critical to successfully solving the problem. Furthermore, there is usually no provision for the operator to volunteer such information. The person may even have different goals than the machine or may not know what the machine's goals are when it is attempting to solve a particular problem. Additional difficulties arise when the human operator accidentally enters the wrong data or when he/she misinterprets a request from the computer. Suchman (1987) discusses the problems of human machine communication at length.

Probably the biggest problem associated with expert systems is that they are brittle. As mentioned above, expert systems can only solve problems that the human expert has seen or remembers to discuss with the knowledge engineer. People (either experts or expert system designers) simply cannot anticipate all of the environmental variability encountered in the world. This leads to the tragic irony of such systems: expert systems are most needed when a problem is difficult, and that is precisely when the expert systems fail. The upshot is that the human operator is left to solve a difficult problem without the benefit of having developed expertise through solving other problems, because those were handled by the expert system!

All of these problems and more arose in a study by Roth, Bennett, and Woods (1987), in which the authors observed technicians using an expert system to troubleshoot an electro-mechanical device. One of the major findings of the study was that only those technicians who were actively involved in the problem solving process and performed activities beyond those requested by the expert system were able to complete the tasks. The technicians who passively performed only those activities requested by the expert system were unable to reach solutions on any but the most trivial tasks.

The above should not be interpreted as a condemnation of all uses of artificial intelligence techniques, however. Indeed, artificial intelligence has greatly advanced our understanding of the capabilities, as well as the limitations, of computational tools. Prudent use of such techniques can greatly enhance the ability of a cognitive engineer to provide operators with powerful problem solving tools.

3.4 EMERGING TECHNOLOGIES

Continued advances in hardware and software technologies will further increase the cognitive engineer's design repertoire. Indeed, there are many emerging technologies that could be profitably used in maintenance job aids. Advances in computer hardware, display hardware, and object modeling all have great potential to improve job aiding capabilities. Each of these is discussed below.

3.4.1 Advances in Computer Hardware

As computer hardware has become smaller and more powerful, there has been a progression to smaller, more portable job aids. Whereas earlier job aids ran on minicomputers, then workstations and personal computers, newer job aids are being designed using laptops. There is no reason to believe that the laptop computer is the smallest, lightest computer that will be developed, however. Indeed, the NCR NotePad has recently been introduced. This computer is pen-based; that is, all input is performed via a pen stylus, rather than through a keyboard or mouse. The NotePad is light enough that it can be easily held in one hand, which greatly facilitates taking it to the maintenance site. The NotePad is relatively quick, it has reasonably large storage capacity, and it has limited handwriting recognition abilities.

An aviation industry working group is currently defining the standards for a `Portable Maintenance Access Terminal' (PMAT) for use in commercial aviation. As currently conceived, the PMAT would connect to the `Onboard Maintenance Systems' of current aircraft and would be used for troubleshooting. Because the emphasis is on portability, it is likely that something similar to the NotePad or a standard laptop computer will be specified.

Another emerging hardware technology is the use of `built-in test equipment' (BITE) in engineered systems, no doubt due in part to the widespread use of microprocessors. BITE likely does not eliminate the maintenance technician, however, because it may be difficult to implement such equipment in mechanical systems or in very complex systems. Indeed, BITE may introduce additional problems for maintenance people because there is a lack of standardization on how BITE should operate; thus, there may be confusion when dealing with similar, but different, BITE. Further complications may arise due to issues of granularity in BITE; BITE may simply indicate that a piece of equipment is not functioning properly, without indicating the specific nature of the malfunction or without indicating which component must be repaired or replaced. Another issue is: What happens when the BITE malfunctions?

3.4.2 Advances in Display Hardware

One of the surveyed systems used a personal computer to control a slide projector for displaying maintenance graphics. Several of the systems used a computer-controlled video disk for such displays. With the advent of digital cameras and compact disc-interactive (CDI) technology, systems with higher fidelity and portability can be achieved. Appropriately designed CDI systems could store many views of the object(s) being serviced, as well as maintenance procedures and information. Indeed, what graphics were displayed would depend on the fault manifestations. Furthermore, well-designed CDI systems would allow the technician to troubleshoot by hypothesizing a failed component and watching how a simulation of the system performed. Similarly, the technician could replace a component in the simulation and see the results. In this manner, the technician could develop expertise more quickly than learning on-the-job (because the technician would have control over what aspects he was learning, rather than relying on whatever malfunction happened to occur).

3.4.3 Advances in Object Modeling

An extension of the three-dimensional model discussed above is virtual reality. Virtual reality has received a lot of attention as a result of the Defense Advanced Research Project Agency's development of the `Pilot's Associate Program' and consists of replacing an operator's view of the `real world' with a simulated view of that world. Thus, real world objects are replaced with simulations of those objects. One possible use of virtual reality would be to allow the maintenance technician to `stand' inside a device, such as an engine, and watch how it functions, both normally and with failed components. The technician could also see the effects of replacing components, similar to the CDI system above, but with the benefit of observing the effects more directly. As with CDI, the technician need not replace the actual system components, but may replace components in the simulation of that system. The uses of virtual reality appear to be limited only by the job aid designer's imagination.

3.5 HUMAN PERFORMANCE IMPLICATIONS OF EMERGING TECHNOLOGIES

While many past approaches to job performance aids sought to replace human expertise with machine expertise, there is a growing appreciation for the importance of human skill. The machine expert paradigm sought to overcome human information processing `limitations' with a computer prosthesis. However, even computers are limited resource processors. A more enlightened approach is to view computers as tools to amplify human capabilities, not overcome limitations. In this sense, computers can be seen to be like other tools, such as telescopes or automobiles: they are instruments which provide additional resources for achieving our needs and desires. Woods and Roth (1988) discussed the above issues and addressed many more cognitive engineering issues inherent to developing systems that have powerful computational abilities.

Technology is not a panacea; each new technology brings with it significant drawbacks, as well as benefits. The challenge to designers is to use emerging technologies to build cooperative systems, in which both the human and the computer are actively involved in the problem solving process. Humans can no longer be regarded as passive `users' of technology, but as competent domain practitioners with knowledge and abilities which are difficult to replace. The following section discusses a study which addressed just such issues.

3.6 A STUDY OF HUMAN PERFORMANCE WITH A COOPERATIVE SYSTEM

A study which addressed some of the human performance issues discussed above was carried out as part of the author's graduate program (Layton, 1992). This study compared three different levels of computer support on the basis of their effects on human performance. Although the domain for which the systems were developed was enroute flight planning, the general principles behind the alternative designs can be applied to developing aviation maintenance aids, as well. The following is a discussion of enroute flight planning, the design concepts behind the three levels of computer support, the method employed for comparing the various systems, the general outcomes of the study, and the implications of those outcomes for developing aircraft maintenance job aids.

3.6.1 Enroute Flight Planning

Enroute flight planning consists of modifying the flight plan of an airborne aircraft in response to changes in the capabilities of the aircraft, to crew or passenger emergencies, to changes in weather conditions, and/or to problems at the destination airport. The study focused on flight plan adaptation in response to changes in weather conditions. From a pilot's perspective, the components important to enroute flight planning include the airplane, possible flight routes, weather conditions, and airline company dispatchers. The pilot is concerned with getting from a given origin to a given destination on time, with a minimum of fuel consumed, while maintaining flight safety. He/she must consider what routes to take (these routes consist of waypoints, or navigational points, and jet routes, the so-called "highways in the sky"), what altitudes to fly, what weather to avoid, and the ever-changing capabilities of the aircraft (e.g., the weight of the plane decreases with fuel consumption; the lighter the plane, the higher it can fly, within limits).

The initial flight plan is rarely followed exactly, due to unforeseen events occurring while enroute. Indeed, minor changes in flight plans are frequently made and major changes are fairly common. These amendments to the original result from the dynamic, unpredictable nature of the `world' in which the plans are carried out. Weather patterns do not always develop as predicted, resulting in unexpected areas of turbulence, less favorable winds, or storms that must be avoided. Air traffic congestion may delay take-off or restrict the plane to lower-than-planned altitudes. Airport or runway closures can cause major disruptions, not just for one aircraft, but for everyone planning on landing at that airport. Mechanical failures, medical emergencies, or other critical problems may delay take-off or may force an airborne plane to divert to a nearby airport.

Furthermore, there are several constraints on the flight plans that can be developed. Planes must maintain a certain separation distance between each other and between thunderstorm cells, as specified in the Federal Air Regulations. Planes must fly along the jet routes. They are also limited to certain altitudes. Over the continental United States, for example, 33,000 feet is an 'eastbound only' altitude. There are also physical limitations: the plane can't fly if it is out of fuel and it can't land at an airport with runways that are too short. Some of these constraints are actually 'soft', in that they may be violated in some circumstances. If, for instance, there is no eastbound traffic, Air Traffic Control (ATC) may allow a plane to fly west at an 'eastbound only' altitude. Similarly, ATC may approve a vector that deviates from the jet routes in order to avoid a storm or to save fuel.

3.6.2 System Design Concepts

It is clear that enroute flight planning is a complex activity, but it is not clear how humans deal with these complexities or how one might program a computer to choose the 'optimum' solution to any given problem. For instance, how does one make tradeoffs between fuel conservation, flight safety, and prompt arrival at the destination? Because pilots make such tradeoffs on a routine basis, one goal of the study was to develop a system to support the pilots in making such decisions. There is a heavy emphasis, therefore, on allowing the pilots to explore "what if" types of questions so that they could gain feedback on the impact of a planning decision on flight parameters.

The three levels of computer support corresponded to successively greater flight planning power. Common to all three systems were: 1. a map display which consisted of the continental United States, the aircraft, and flight routes; 2. a representation of a flight log, which included the flight route and altitudes; and, 3. a display of flight parameters. These three items were displayed on two monitors. Figure 3.1 depicts the map displays and controls, and Figure 3.2 depicts the flight log display and controls and the flight parameter display. The pilot could elect to display weather data, waypoints, and jet routes on the map display. The lowest level of enroute flight planning support provided the pilot with the ability to sketch proposed flight plans on the map, in accordance with the waypoint and jet route structure. The latter condition required a pilot to sketch routes one waypoint at a time. Once the pilot completed a proposed flight plan, in terms of geographic location, the computer responded with various flight parameters, such as time of arrival and fuel remaining at the destination. The computer also indicated whether the flight was predicted to encounter any turbulence and the severity of that turbulence. The computer also proposed the most fuel efficient vertical flight profile for the proposed route. This form of support encouraged the pilots to propose options and see their effects on flight parameters. This form of support is referred to as the `sketching only' system.

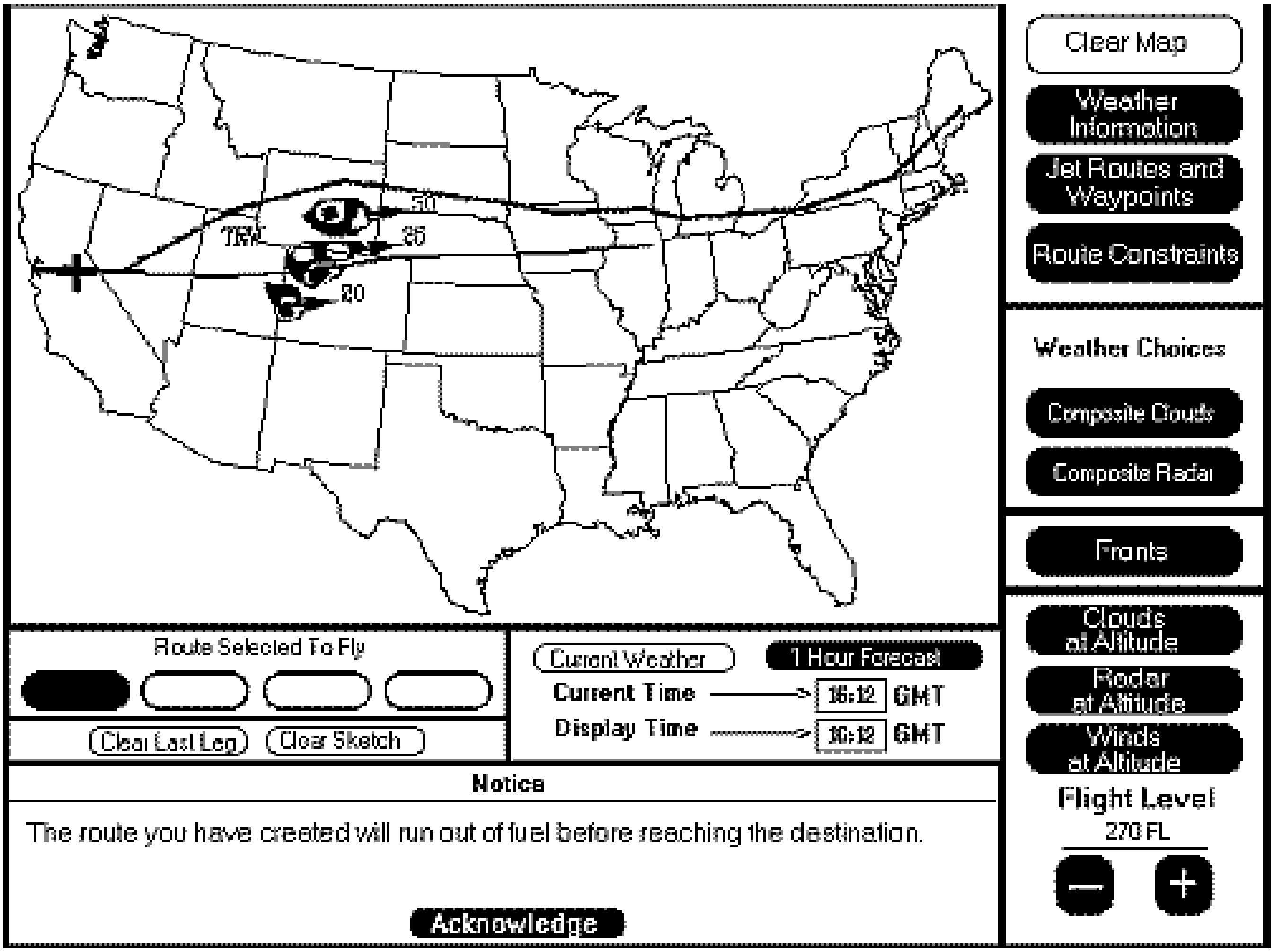

Figure 3.1 Left Monitor Displays and Controls

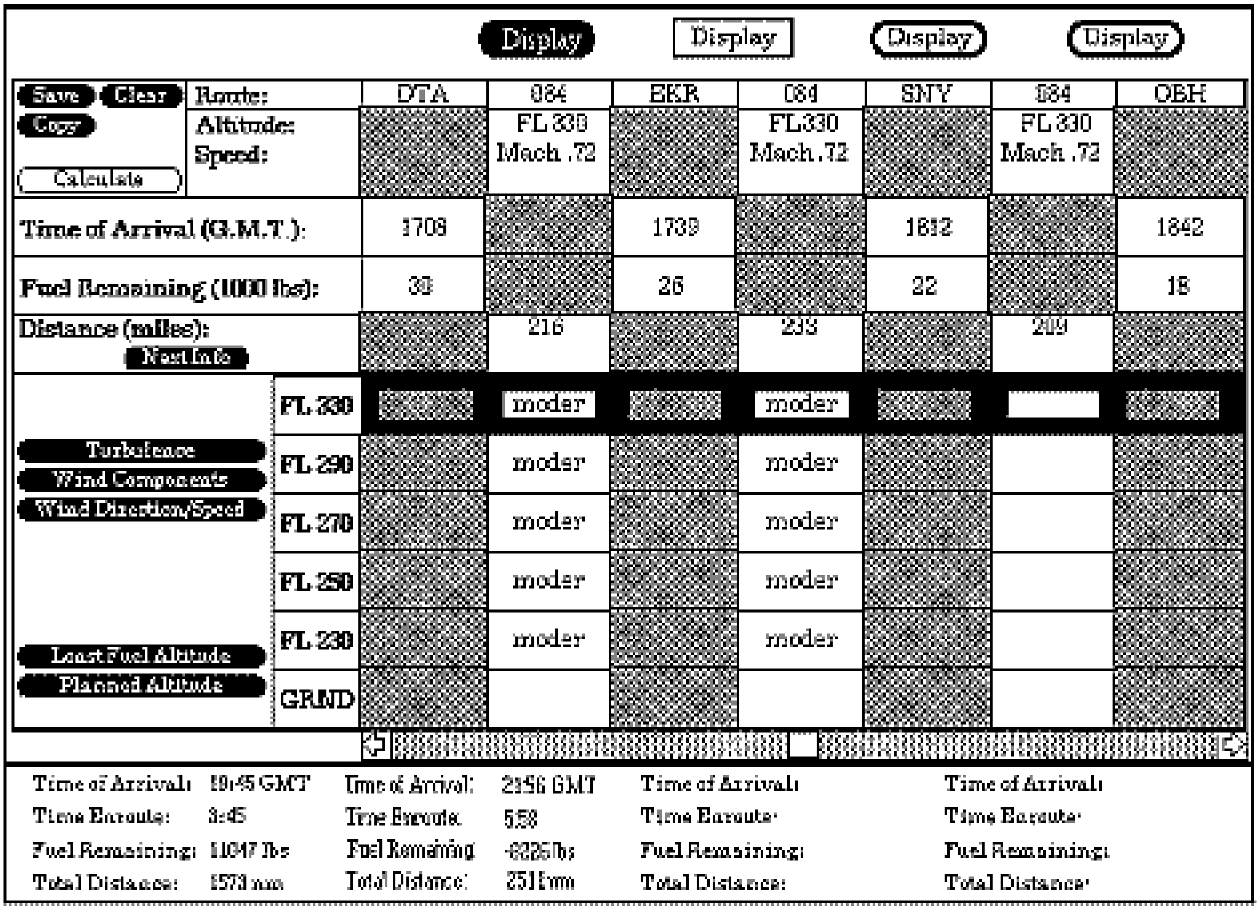

Figure 3.2 Right Monitor Displays and Controls

The next level of computer support incorporated the sketching form of interaction, but also included a method for placing constraints on a desired solution and allowing the computer to propose a solution which satisfied those constraints. For instance, the pilot could place limits on the maximum severity of turbulence and precipitation encountered, and could specify the desired destination. The computer would then perform a search of the data and solution spaces and propose a route that satisfied the pilot's constraints while minimizing fuel consumption. This proposed route would include both the geographic route and the vertical profile, along with its associated flight parameters. This form of flight planning causes the pilot to plan at a more abstract level than the sketching form of interaction, because the pilot is able to think about the characteristics of a desired solution while the computer handles the lower level details of specific routings. Using the sketching tool, the pilot was free to modify the route proposed by the computer and note the impact of such changes on the flight parameters. This second level of planning can be roughly construed to be a form of consultation system because the computer can be asked for its advice on a problem; it is referred to as the `route constraints and sketching' system.

The highest level of support corresponds to an expert system that automatically solves a problem as soon as it is detected; upon loading the scenario information, the computer would propose a solution which minimized fuel consumption and satisfied the constraints of encountering no turbulence and no precipitation, as well as arriving at the planned destination. As in the previous level of support, the computer would propose both the geographic route and altitude profile, along with the corresponding flight parameters. If desired, the pilot could also request a solution from the computer based on different constraints, and he could sketch his own solutions.

3.6.3 Study Method

Thirty male commercial airline pilots were randomly assigned to one of three treatment conditions, wherein each condition consisted of one of the three forms of computer support described above. There were ten subjects in each condition. Each pilot was trained for approximately one hour on his system prior to solving four enroute flight planning cases. Each case consisted of a planned flight that was disrupted because of a change in weather conditions. The task for the pilot was to decide what to do in each situation. All of the pilots solved the four cases in the same order. It took approximately an hour and a half to solve the four cases.

3.6.4 Study Results

Each of the four cases provided some interesting insights into the influences of computer tools on human behaviors. The overriding results of each of the four cases are discussed below.

3.6.4.1 Case 1 General Results

In the first case, most of the subjects in the `route constraints and sketching' and the `automatic route constraints, route constraints, and sketching' conditions chose to fly the computer-suggested route (as expected). However, the `sketching only' subjects tended to choose routes that were more robust; that is, these subjects put more distance between the aircraft and the storm. These subjects commented that they would like to have more distance from the storm than afforded by a more direct route (such as the one suggested by the computer in the other two treatment conditions). Furthermore, the `sketching only' subjects were more apt to explore multiple routes and multiple types of routes, than were the subjects in the other two groups. These results suggest that the sketching form of interaction caused the subjects to consider the data more carefully than did the route constraints tool. One reason for this result is that the sketching tool gave the subjects the opportunity to consider the relationships of various route options and the weather at several points and to consider the robustness of those options given the uncertainties associated with weather. The constraints tool, on the other hand, did not encourage such behavior, and, indeed, the subjects using that tool may have been under the impression that the computer was considering the robustness of routes, when in fact it was not. If the sketching tool encouraged more careful examination of the data than did the constraints tool, and this behavior persisted, one could imagine situations wherein the constraints tool could lead to bad decisions.

3.6.4.2 Case 2 General Results

While Case 1 provided evidence for the benefits of tools that make the operator the sole decision maker, Case 2 provided evidence to the contrary. In Case 2, the `sketching only' subjects had significant difficulty, as a group, in searching the relatively large data and solution spaces. Many of the routes explored by these subjects passed through strong turbulence. Indeed, four of these ten subjects chose deviations that exacted a high fuel consumption cost, either because they could not find a more efficient route around/through the weather or because they did not examine wind data which would have indicated that their chosen route encountered strong head winds. By contrast, the subjects in the `route constraints and sketching' and `automatic route constraints, route constraints, and sketching' groups successfully used the computer to rapidly find a fuel efficient deviation that avoided all of the weather. Furthermore, nearly all of the subjects who chose an inefficient deviation later stated that they preferred the more efficient deviation suggested by the computer to the other groups.

3.6.4.3 Case 3 General Results

As noted in the discussion of Case 1, the `sketching only' subjects chose rather different solutions than did the `route constraints and sketching' and the `automatic route constraints, etc.' subjects. Furthermore, it was hypothesized that the `sketching only' subjects were more involved in the problem solving process than were the subjects in the other two groups. The third case was designed to address the issues related to what happens when the automatic tools suggest questionable solutions: Does the operator recognize that the solution may not be appropriate? Assuming the operator does recognize that the solution is inappropriate, can he readily come up with a better solution?

In Case 3, the computer suggested two different routes in the `route constraints and sketching' and `automatic route constraints, etc.' conditions, depending upon the constraints placed on it. One deviation passed between two large thunderstorm cells of a volatile storm, which is a risky practice, at best; this route was suggested on the basis of no turbulence and no precipitation. The other route avoided the bulk of the weather, at the cost of slightly higher fuel consumption and a small amount of turbulence; this route was suggested on the basis of light chop (or greater) turbulence and light (or heavier) precipitation. The trend in this case was for the `route constraints and sketching' and the `automatic route constraints, route constraints, and sketching' subjects to choose the first route more frequently than the `sketching only' subjects. If these subjects had not examined both routes, then it would suggest that these subjects were simply over-reliant on the computer. However, several of the subjects in the `route constraints and sketching' and `automatic route constraints, etc.' groups examined both routes before choosing the more risky route; thus, these subjects chose a risky route despite evidence that it may have been a poor choice and that a better option existed. These subjects nearly unanimously changed their minds when later questioned about their decisions.

With few exceptions, the `sketching only' subjects planned very conservative deviations that completely avoided the weather. However, the `sketching only' subjects had considerable difficulty in finding acceptable deviations. In fact, one subject chose a deviation that was predicted to cut into his required landing fuel reserves prior to arrival at the destination. Thus, even though the `sketching only' subjects may have considered the data very carefully, the problem was sufficiently complex that they would have benefitted from some computer assistance.

3.6.4.4 Case 4 General Results

Case 4 provided some interesting results with regard to individual differences and with regard to the influence of computer recommendations. The `sketching only' and `route constraints and sketching' subjects were nearly evenly divided between a fuel efficient deviation and a robust deviation. When asked about his decision, one of the `sketching only' subjects made the comment that the decision depended on the person's role in flying the aircraft at the time: if the captain were flying that leg, he would go one way so that he could look at the storm, but if the first officer were flying that leg, he'd go the other way around so that he could see the storm. Obviously this is an extreme example, but it underscores the role of individual differences in decision making.

Unlike the subjects in the other two groups, the `automatic route constraints, route constraints, and sketching' subjects, were more likely to choose the computer-suggested, economical route, even when they had explored both routes. Combined with the results of Case 3, this result suggests that the computer exerts a strong influence on decision making when it recommends a solution at the onset of a problem.

3.6.5 Study Conclusions

The goal of the research was not to determine which particular version of an enroute flight planning tool resulted in the best human performance. Rather, one goal was to see how human behaviors were influenced by the tools available. Subjects who had multiple tools available to them (the `route constraints and sketching' subjects and the `automatic route constraints, route constraints, and sketching' subjects) were able to use them to develop alternative plans. In fact, there were many instances in which the solution recommended by the computer did not meet the needs of the pilots, so the pilots developed their own plans through sketching. Thus, not only is there a need for tools that allow the operator to go beyond a computer's solution, but there is a need to support individual differences, as well.

The subjects who had only the sketching tool available to them closely examined the available data. As a result, these subjects often planned robust deviations that would not need to be altered if there were further changes in the weather. Where these subjects ran into difficulties, however, was in situations in which there were a lot of potential solutions and there was a large amount of data. In such situations, these subjects had trouble finding appropriate solutions. Indeed, some of these subjects made poor decisions because of these difficulties. The subjects who had some form of computer assistance were able to more efficiently search these spaces, but with some costs.

The tool that automatically suggested a solution to the problem as soon as it was detected did not encourage the subjects to closely examine the data. While this fact did not cause problems in some cases, it clearly did lead to bad decisions in others. Furthermore, the automatic tool's influence on decision making went beyond simple over-reliance to the point where it shifted attention from data which were important to making a good decision.

3.6.6 Implications for Maintenance Job Aids

The conclusions outlined above can be readily applied to developing maintenance job aids. For instance, one of the conclusions is that there is a need for tools that allow an operator to go beyond a computer's solution. As discussed above, particularly with regard to Case 3, and as discussed by Roth, Bennett, and Woods (1987) and Suchman (1987), operators frequently have knowledge or information which is not available to the computer, but which is critical to making a good decision. By giving the authority and responsibility for decision making to the operator, and by providing a tool which supports the operators activities (rather than the other way around), the operator is free to explore solutions that may not have been designed into a machine expert.

Another conclusion reached by the above study was that the form of tool that required a person to make a series of decisions (the sketching tool) encouraged the operator to think hard about the problem and to consider the available data at a deeper level, than did the form of tool that encouraged the operator to make a single `yes' or `no' decision (the automatic route constraints tool). In this regard, the conclusion supports the notion that designers need to "keep the person in the loop".

However, another conclusion of the above study was that "keeping the person in the loop" did not provide adequate support in some situations. Indeed, in some of the cases (such as Cases 2 and 3) some of the operators were simply unable to find adequate solutions on their own. These operators could have used some help from a computer in exploring solution possibilities. In such situations this is rarely a reflection of human `limitations', rather it is an indication of the difficulty of the problem. In maintenance, for instance, diagnosing multiple, interacting faults is a difficult problem. One symptom may be characteristic of several faults, or one fault may mask the presence of another. A tool which helps to focus the diagnostician's attention and eliminate false leads would be very beneficial.

Finally, it is important to realize that each person has a different style of decision making; two people who complete the same training course on a given method for dealing with a problem may use slightly different approaches. Such differences are likely to increase with experience as each person learns methods that consistently work for him/her. Indeed, experts often use several different approaches to solving truly difficult problems because each approach has unique limitations as well as unique benefits. For instance, knowledge of thermodynamics may help localize a fault to a heat exchanger, but knowledge of circuits may lead one to test the power supply to the heat exchanger, as well. Thus, tools need to be flexible to support such individual differences, rather than use a single, lockstep approach, as in the case of `expert' systems. (Note that although some expert systems do incorporate the observable components of such methods, they do not allow the operator direct access to those methods. Because the knowledge and capabilities of such systems are necessarily incomplete, the systems are `brittle' in the face of difficult problems, as discussed above in **Section 3.4**)

3.7 RESEARCH AND DEVELOPMENT PLAN

The above discussion points to the challenge for cognitive engineers involved in designing maintenance job aids: build systems that capitalize on both human strengths and computer strengths so that task performance is improved. As outlined above, because of relatively recent advances in hardware and software, it is possible to use sophisticated computational techniques (e.g., cooperative system techniques) to develop real time, computer-based job aids for a wide range of technical tasks. Furthermore, hardware like the NCR NotePad will make it easier for people without previous computer training to use such job aids. We are working with the Flight Standards Service of the FAA to develop a Portable Performance Support System (PPSS) to aid Aviation Safety Inspectors in their daily activities. The initial focus of this effort is on the tasks performed by Airworthiness (maintenance) Inspectors, particularly the Ramp Inspections task. Inspectors need access to many of the same types of information that maintenance technicians use. Inspectors must also document their activities and the outcomes of those activities. We are taking a three Phase approach to developing a PPSS: Phase I, already underway, will identify a prospective task and perform an information needs analysis for that task; during Phase II we will design and develop a prototype PPSS for the task; and we will create a plan for the development of the prototype into a fully functional system during Phase III. Each of these phases is described more fully below.

3.7.1 Phase I: Problem Definition and Information Needs Analysis for Aviation Safety Inspectors

Goal: Identify a typical task for which a computer-based job aid is an appropriate application and conduct appropriate information needs analysis to define the work environment and information needs for aviation safety personnel.

We are working with the personnel of the Fort Lauderdale Flight Standards District Office (FSDO) to help identify an appropriate task for computer-based job aiding. Such a task should be one which is typical for the personnel, but which may require some experience to attain proficiency. This Phase of the research is an ongoing process continued throughout the life of the project.

The task initially proposed to the Fort Lauderdale FSDO is one of an Airworthiness Inspector performing Ramp Inspections. Ramp Inspections are used to verify aircraft airworthiness just prior to a planned flight. The inspectors walk around the aircraft, identifying problem areas and documenting those problems on a Program Tracking and Reporting Subsystem (PTRS) form (if an aircraft meets safety standards, that information is noted on the same form). The PTRS form is used to document all activities in which inspectors are involved; such activities include accident/incident investigation, airman certification, flight school certification, etc. Inspectors also use paper-based "job aids", which are essentially checklists, to assist them in their activities. Filling out forms and following checklists are the types of activities for which the NotePad was designed. Therefore, such tasks are amenable to transfer to pen-computer technology. Furthermore, the computer allows multiple forms to be linked together such that entries in one form are automatically propagated to all related forms; this approach would eliminate the duplicate entry of data which currently occurs. Finally, PTRS forms are currently recorded in paper format and given to data entry clerks who must interpret the inspector's handwriting and transfer the data to the FSDO's local computer-based database (which feeds into the national PTRS database). The PTRS data collected on a PPSS will be in a format that can be directly transferred into a FSDO's local PTRS database, thus eliminating the intermediate manual data entry step.

Inspectors must also have access to large amounts of information, such as Federal Aviation Regulations, Inspector's Handbooks, Airworthiness Directives, Advisory Circulars, etc. Whereas inspectors must currently retain hard copies of such information or refer to the FAA mainframe repository, it can become cumbersome to access and track this information. This suggests that a hypermedia on-line documentation system can be beneficial to the inspectors. This system can run off either the NotePad's internal hard drive or an external CD ROM device. Such an on-line documentation will facilitate rapid access to up to date information.

Based on initial conversations with the Flight Standards Service, it appears that a PPSS will:

- Provide inspectors with an integrated, linked form system
- Provide a means to reduce data entry performed by clerks
- Provide on-line documentation, including FARs, handbooks, etc.

3.7.2 Phase II: Design and Development of a Prototype Portable Performance Support System

Goal: Build and demonstrate a prototype Portable Performance Support System to support Aviation Safety Inspectors doing Ramp Inspections.

This phase will involve several iterations of development and demonstration. Rapid prototyping of the PPSS will permit us to demonstrate the system to inspectors for quick feedback about the design and content of the system. We will work closely with the inspectors during this phase to ensure the accuracy of the information and the usability of the PPSS. While these evaluations will primarily involve the airworthiness inspectors, it is extremely helpful to have other inspectors evaluate the PPSS, because they can provide a fresh perspective and would be likely to identify additional areas for improvement.

3.7.3 Phase III: Create a Plan for the Development of the Prototype System into a Fully Operational System

Goal: Create a plan to convert the prototype PPSS into a fully operational system for evaluation and integration into the work environment.

This phase will require a formal review of the prototype PPSS to identify its strengths and weakness. Following this review, a plan will be developed to fully implement the PPSS. The plan will include the design of a study to evaluate the effectiveness of the PPSS in the work environment.

3.8 SUMMARY

Several past approaches to maintenance job aiding were discussed with respect to their impact on human performance. Such approaches have typically used a `machine expert' to guide technicians through the maintenance process. However, the `machine expert' paradigm has met with limited success in operational environments because of problems with unanticipated variability in the environment (or `brittleness'), extra-machine knowledge, and inflexibility. An alternative philosophy to developing systems was presented, cooperative systems, in which both the human and the computer are actively involved in the problem solving process. This philosophy advocates a change in perspective toward computers as tools to assist people in their work, rather than as prostheses to overcome human `limitations'. The cooperative problem solving paradigm capitalizes on the strengths of humans and computers in order to improve the performance of both. A study which compared different versions of a job aiding system designed with using this philosophy was presented, along with implications for developing maintenance job aids. Finally, a plan for developing a portable performance support system for aviation safety inspectors was presented.

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Chapter 3
Appendix
Annotated References

Aerospace maintenance. (1986, December). *Aerospace America*, p. 46.

Article describes artificial intelligence software that continuously monitors systems, isolates faults, and indicates fault presence, on Boeing B1B bomber. The system is projected to save $260 million in maintenance. Also discusses an F/A-18 on board maintenance processor that creates data files in flight to be later processed by an expert system. See also "AI to help keep..."

Ahrens, R. B., Marsh, A., & Shannon, P. A. (1984, November). 3B20D computer: Maintenance with a mind of its own. *Record,* pp. 16-19.

Discusses replacement of panel status indicators with microcomputer status indicators for maintenance.

AI to help keep aircraft flying. (1986, June 12). *Machine Design*, p. 4.

`Avionics Integrated Maintenance Expert System' (AIMES) was developed by McDonnell Douglas to monitor circuit cards in flight on F/A-18 Hornet. AIMES can identify which card has a failed component. See also "McDonnell Douglas..."

Armor, A. F. (1989, July). Expert systems for power plants: The floodgates are opening. *Power Engineering,* pp. 29-33.

Discusses the future of expert systems in the power industry, particularly for failure prevention and diagnosis.

Artificial intelligence to aid in war on potholes. (1985, December 12). *Engineering News-Record,* p. 215.

Describes research and development efforts at the University of California on a system for diagnosing and repairing pavement faults.

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A concept paper that distinguishes between `shallow models' (models that use empirical data to detect previously observed faults) and `causal models' (models that reason from functional models of system).

Barney, C. (1985, December 23). Expert system makes it easy to fix instruments. *Electronics,* p. 26.

Describes an expert system for diagnosing, repairing, and calibrating electronic instruments. The system has been applied to a signal-switching system. The system is VAX based.

Benedict, P., Tesser, H., & O'Mara, T. (1990, June). Software diagnoses remote computers automatically. *Automation,* pp. 46-47.

Grumman Data Systems and Grumman Systems Support developed a `Remote Diagnostic System' (RDS) that diagnoses computer malfunctions. The VAX-based system is fully automatic; there is no human involved in the diagnosis process. The RDS prints a prioritized list of suspect printed-circuit boards with explanations on how the conclusions were reached. RDS can also serve as a consultant to a human diagnostician. RDS was designed to perform with the proficiency of an intermediate level diagnostician and to serve as the tool to be used first in diagnosing problems. The RDS combines rule- and model-based reasoning.

Bertheouex, P. M., Lai, W., & Darjatmoko, A. (1989). Statistics-based approach to wastewater treatment plant operations. *Journal of Environmental Engineering, 115,* 650-671.

Describes an expert system for daily operation of wastewater treatment plant. Uses d-Base III and Lotus 1-2-3.

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The `Advanced Diagnostic and Predictive-Maintenance System' is a system for monitoring and diagnosing problems at nuclear and fossil power plants. The system also schedules `predictive maintenance', wherein maintenance is scheduled based on performance trends. The article describes system modules, with an emphasis on trend monitoring and preventive maintenance.

Bretz, E. A. (1990, July). Expert systems enhance decision-making abilities of O&M personnel. *Electrical World,* pp. 39-48.

Overview of several expert systems. Houston Lighting and Power Co. uses three systems: a materials management system that tracks spare parts and supplies, a maintenance management controls system that consolidates and standardizes methods for requesting and tracking maintenance, and an expert management scheduling system that generates reports and creates schedules.

Westinghouse Electric Corp. developed `Argus', an alarm response advisor. Argus details alarm causes and required responses. The system collects data on-line, diagnoses problems, and makes recommendations.

Computational Systems, Inc. developed an expert system for vibrational analysis of rotating machinery.

Chubu Electric Power Co. and Toshiba Corp. developed a maintenance support expert system for large turbine generators. The system handles complex and time-consuming tasks. A engineer enters a failure into the system and the system responds with other damages that may result from a suspected root cause, it gives standard repair methods and design specifications, and it displays the most likely failure sources.

Chubu Electric Power Co. and Mitsubishi Heavy Industries, Ltd. developed an expert system for boiler failure analysis and maintenance planning. Failure analysis produces the most probable causes, guidelines for inspection, items to be investigated, repair methods, and suggested preventive maintenance. A maintenance planning subsystem automatically prepares daily repair schedules, work estimation plans, and work specifications.

Byrd, T. A., Markland, R. E., & Karwan, K. R. (1991, July-August). Keeping the helicopters flying--using a knowledge-based tank support system to manage maintenance. *Interfaces,* pp. 53-62.

Discusses a knowledge-based system which generates reports for helicopter maintenance. The system tracks helicopters and notifies maintenance staff of which helicopters are nearing regular inspections or special inspections. Reports specify the time-between-overhaul components that will require maintenance soon and give flying schedules prioritized on mission and maintenance needs. The system replaced a cumbersome manual system.

Callahan, P. H. (1988, January-February). Expert systems for AT&T switched network maintenance. *AT&T Technical Journal,* pp. 93-103.

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Describes an expert system for diagnosing switch mode power supplies by using a functional model.

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Discusses a pc-based preventive maintenance and training system for water mains.

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Discusses the In-flight Engine Condition Monitoring System (IECMS) as a foundation for `on-condition' maintenance of fighter aircraft engines. On-condition maintenance actions are undertaken based on actual engine conditions, rather than as preventive maintenance. IECMS monitors and records engine performance parameters, notifies the pilot when caution should be exercised, and records maintenance codes when an operating limit has been exceeded. Data are stored on a removable tape cartridge. The article features several examples of data indicating normal and abnormal operating conditions.

Culp, C. H. (1989). Expert systems in preventive maintenance and diagnostics. *ASHRAE Journal, 31*, 24-27.

Sales article on using expert systems for heating, ventilation, and air conditioning maintenance.

Dallimonti, R. (1987, June 18). Smarter maintenance with expert systems. *Plant Engineering,* pp. 51-56.

An introduction to the prospects of using expert systems for maintenance. Surveys systems from Hughes Aircraft Company, Rockwell International, and Campbell Soup Company.

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Extension of 'General Diagnostic Engine' discussion in de Kleer and Williams.

de Kleer, J. & Williams, B. C. (1987). Diagnosing multiple faults. *Artificial Intelligence, 32,* 97-130.

An academic discussion of a 'General Diagnostic Engine' for diagnosing multiple faults. Combines model-based prediction with sequential diagnosis to propose measurements to diagnose faults.

Dobson, R., & Wild, W. (1989, May). Plant's computerized maintenance system improves operations. *Power Engineering,* pp. 30-32.

A Lotus Symphony-based system automatically processes maintenance clearances for power plant.

Dohner, C. V., & Acierno, S. J. (1989, August). Expert systems for gas-turbine powerplants passes first tests. *Power*, pp. 63-64.

Citing the limited amount of troubleshooting and diagnostic information in the manufacturer's maintenance manuals, EPRI developed an expert system for gas-turbine power plants. A portable pc uses voice recognition and synthesis and links to a pc in control room. The control room pc drives a video disk player and a printer.

Doorley, R. (1988, August). Hydraulic troubleshooting using an expert system. *Hydraulics & Pneumatics*, pp. 91-92.

Discusses the `MindMeld' system for steel mill hydraulic equipment maintenance. MindMeld uses test equipment data and operator information to determine the likely cause of a problem. See also Doorley, (1989).

Doorley, R. B. (1989, June 22). Expert systems probe hydraulic faults. *Machine Design,* pp. 89-92.

More on the `MindMeld' system for hydraulic equipment troubleshooting in steel mills. The pc-based system focuses on faults that are difficult to locate and which require extensive dismantling of machinery if left unrecognized.

Expert system from AT&T Bell Laboratories is an `ACE' at telephone cable analysis. (1983, October). *Record*, p. 1.

The `Automated Cable Expertise' system identifies trouble spots in telephone cable systems. ACE gives repair histories of problematic areas and suggests corrective action. The system is automatic and runs daily.

Expert system guides tube-failure investigations. (1989, August). *Power*, p. 85.

Discusses an expert system for boiler tube failure diagnosis and corrective action (including non-destructive examination, repair, welding, metallurgical tests, references). The system an be used to determine tube failure mechanisms. The system also has a database for tube history, design, inspection, maintenance and it provides context-sensitive information about repair practices. PC-based, linked to a slide projector. See also Smith, (1989, December).

Expert system probes beneath the surface. (1990, January). *Mechanical Engineering*, p. 112.

Britain's Central Electricity Generating Board developed an expert system for monitoring and analyzing vibration patterns of turbine generators. The expert system uses `deep knowledge' of cause and effect relationships in turbine generators. The goal in developing the system was to transfer initial analysis from specialist staff to engineering/operations staff.

Expert systems to hone jet engine maintenance. (1986, April 21). *Design News,* pp. 36-38.

Describes an expert system to diagnose engine malfunctions and facilitate preventive maintenance by predicting when parts must be replaced. The system switches maintenance from a scheduled replacement basis to an `as-needed' replacement basis. It uses qualitative and historical maintenance data. The pc- based system was developed by the General Electric R&D Center in conjunction with GE's Aircraft Engine Business Group for the Air Force.

FAA and NASA design program to improve human performance. (1989, May 29). *Aviation Week & Space Technology*, p. 115.

Outlines joint FAA and NASA effort to sponsor human factors research.

Foley, W. L. , & Svinos, J. G. (1989). Expert advisor program for rod pumping. *Journal of Petroleum Technology, 41*, 394-400.

`EXPROD' is an expert adviser program for rod-pumping diagnostics used by Chevron. The program analyzes field data to identify equipment problems and recommend solutions. EXPROD uses statistical pattern recognition in conjunction with diagnostic rules. Some worker expertise is still required to diagnose problems. EXPROD runs on a microcomputer.

Folley, J. D., & Hritz R. J. (1987, April). Embedded AI expert system troubleshoots automated assembly. *Industrial Engineering*, pp. 32-35. Discusses an expert system to assist technicians in diagnosing a clutch assembly machine. The expert system uses a computer-controlled video disk to indicate what the technician should be doing or looking at.

Fault lamps above stations indicate malfunctioning assembly stations. The technician takes a monitor, a two-button control, and a maintenance cart to the faulty station and plugs into a junction box connected to the computer and video disk player. The technician selects the station or procedure from a menu and the computer specifies tests or actions with graphics. The technician supplies data and the computer specifies the next action.

GM unveils "Charley", an expert machine diagnostic system. (1988, May). *I&CS*, pp. 4-7.

Describes vibration analysis expert system for production machinery with rotating components. Charley helps mechanics: 1. identify parts that need repair; 2. repair or adjust equipment prior to failure; 3. speed up diagnosis; 4. distribute expertise; and 5. avoid fixing functioning equipment. See also Stovicek, (1991).

Gunhold, R., & Zettel, J. (1986). System 12 in-factory testing. *Electrical Communication, 60(2)*, 128- 134.

Describes a diagnostic expert system for ITT System 12 printed circuit board assemblies.

Hartenstein, A. (1988, January). Computer system controls all maintenance activities. *Public Works*, p. 60.

The system maintains several types of records and schedules preventive and corrective maintenance. It also issues work orders and monitors progress. It is a database system.

Hill, S. (1990, February). Ask the expert. *Water & Pollution Control*, pp. 12-13.

Concept paper that discusses possibilities of expert systems to design wastewater treatment facilities and control such plants.

Hughes, D. (1988, March 7). Digital develops special applications to meet diverse aerospace needs. *Aviation Week & Space Technology*, pp. 51-53.

Jet fighter uses AI as troubleshooter. (1986, July 21). *Design News*, p. 20.

More on AIMES. See also "McDonnell Douglas..."

Keller, B. C. & Knutilla, T. R. (1990, September). U.S. Army builds an AI diagnostic expert system, by soldiers for soldiers. *Industrial Engineering*, pp. 38-41.

Describes the `Pulse Radar Intelligent Diagnostic Environment' for troubleshooting the Pulse Acquisition Radar of a Hawk missile system.

King, I. J., Chianese, R. B., & Chow, M. P. (1988, December). Plant diagnostics relies on AI transmissions from remote site. *Power*, pp. 57-60.

Describes a suite of on-line power plant diagnostic systems developed by Westinghouse Electric Corp. Development goals were to maximize availability and efficiency and reduce forced-outage rates of turbine generators. The systems identify worn or damaged components early. `ChemAID' diagnoses problems in the steam/water cycle; it determines the type, severity, and location of water chemistry problems. ChemAID assists the operator in determining the need for immediate or delayed action. It can also serve as a consultant.

`TurbinAID' diagnoses problems in steam turbines. It diagnoses the condition and thermodynamic performance of turbines and reports current and target performance parameters.

`GenAID' monitors trends for gas-cooled generators.

Kinnucan, P. (1985, November). A maintenance expert that never sleeps. *High Technology*, pp. 48-9.

The `Intelligent Machine Prognosticator' (IMP) is an expert system for maintenance of an epitaxial reactor (equipment that `grows' additional silicon crystals on silicon wafers). IMP diagnoses faults and recommends repair procedures. The system was developed because vendor support was difficult to obtain. IMP reportedly reduced repair time by 36%.

Kolcum, E. H. (1989, January 2). Growing flight, maintenance simulator market attracts many competitors. *Aviation Week & Space Technology*, pp. 91-93.

Discusses proposed military expenditures on simulators for maintenance training.

Layton, C. F. (1992). An investigation of the effects of cognitive tools on human adaptive planning in the domain of enroute flight planning. Doctoral dissertation, The Ohio State University, Columbus, OH.

Discusses a study which compared three different levels of computer support for enroute flight planning. The study compared the behaviors of thirty professional airline pilots assigned randomly to each of three treatment conditions (ten subjects per condition, each condition consisted of a different form of computer support). The subjects were trained on system use prior to solving four enroute flight planning scenarios. The focus of the research was not on the principles used to design the enroute flight planning systems, rather it was on what characteristics the designs shared and what characteristics were unique to a particular system. The purpose of the research was to study how these three system designs, as examples of broader classes of planning assistance tools, affected enroute flight planning, as an example of adaptive planning. The goals of this study were to develop a better understanding of the adaptive planning process and to develop recommendations for designing tools to support that process.

Maintenance expert in a briefcase. (1986, April). *High Technology*, p. 9.

`Mentor' is a portable expert system for routine maintenance and diagnosis of air conditioners. Mentor keeps service records of each piece of equipment. The emphasis is on preventive maintenance.

Majstorovic, V. D. (1990, October). Expert systems for diagnosis and maintenance: State of the art. *Computers in Industry*, p. 43-68.

Discussion of typical expert system components and survey of diagnosis and maintenance expert systems. Discusses expert systems for maintenance of flexible manufacturing systems.

McDonnell Douglas flight tests AI maintenance data processor. (1986, February 17). *Aviation Week & Space Technology*, p. 69.

Describes `Avionics Integrated Maintenance Expert System' (AIMES) for F/A-18. AIMES gathers aircraft data and creates flight files for later analysis. Production rules detect and isolate avionic failures at the electronic card level. Analysis provides fault data, the card name, and the reasoning that led to the fault isolation conclusion. AIMES is a self-contained on board system with a microprocessor and a data storage cassette. AIMES includes BITE. See also "AI to help keep..."

McDowell, J. K., & Davis, J. F. (1991). Managing qualitative simulation in knowledge-based chemical diagnosis. *AIChE Journal*, *37*, 569-580.

An academic discussion of an approach for dealing with multiple interacting faults with an expert system.

Melhem, H. G., & Wentworth, J. A. (1990, March). FASTBRID: An expert system for bridge fatigue. *Public Roads*, pp. 109-117.

`Fatigue Assessment of Steel Bridges' is a training aid for bridge inspection and planning remedial actions. It is also an advisory system for evaluation of bridges. The advisory system helps organize fatigue inspection, evaluate inspection results, and determine a course of action.

Miller, D. M., Mellichamp, J. M., & Wang, J. (1990, November). An image enhanced, knowledge based expert system for maintenance trouble shooting. *Computers in Industry*, pp. 187-202.

Describes an expert system for diagnosis of the electrical/hydraulic system of an electric utility vehicle. The vehicle system is difficult to diagnose because faults can be masked by behavior of equipment. The expert system displays a limited number of photographs of a vehicle. The expert system is pc based.

Miller, F. D., Rowland, J. R., & Siegfried, E. M. (1986, January). ACE: An expert system for preventive maintenance operations. *Record,* pp. 20-25.

Discusses the `Automated Cable Expertise' (ACE) system for telephone cable analysis. ACE is an automatic report generator which runs daily. Sell also "Expert system from AT&T Bell Laboratories...".

Moradian, S., Thompson, E. D., & Jenkins, M. A. (1991, May). New idea in on-line diagnostics improves plant performance. *Power*, pp. 49-51.

Discusses Westinghouse expert systems, particularly GenAID. See also King, Chianese, and Chow (1988, December).

Nelson, B. C., & Smith, T. J. (1990). User interaction with maintenance information: A performance analysis of hypertext versus hardcopy formats. *Proceedings of the Human Factors Society 34th Annual Meeting,* 229-233.

Research paper which discusses experimental results of comparing hypertext versions of maintenance manuals with hardcopy versions of those manuals. Subjects were slower with hypertext than hardcopy, but preferred hypertext. Enhanced versions of manuals (hypertext and hardcopy) improved access to information and comprehension of that information, but subjects did not recognize improvements.

Nordwall, B. D. (1989, June 19). CTA develops new computer system to speed civil aircraft maintenance. *Aviation Week & Space Technology,* pp. 153-157.

Describes the `Automated Maintenance Management System' (AMMS) and the `Mobile Enhanced Comprehensive Asset Management System' (MECAMS) developed by CTA, Inc. The AMMS collects inflight information on F/A-18 aircraft engines and stores it on a floppy disk for later analysis by MECAMS. MECAMS runs on a laptop computer connected to a minicomputer, which in turn could be connected via satellite or phone link to a database of troubleshooting and logistics information. MECAMS first identifies periods when engine performance parameters are exceeded, then it assists technicians in troubleshooting and maintaining the engines. CTA indicated that the F/A-18 engine system was a proof of concept and was proposing that the same system could be extended to civil aircraft engines and avionics.

NYNEX cuts costs in 40 offices using expert system. (1990, September). *Industrial Engineering,* pp. 81-82.

`Maintenance Administrator Expert' (MAX) diagnoses problems with residential and small business telephone service. MAX interprets trouble report data in 5-10 sec. as opposed to the 5-10 min. a human requires. MAX dispatches the correct technician and reduces false dispatches. The system reportedly saves $4-6 million/yr. MAX was developed by NYNEX Science and Technology Center and runs on a Sun 3/260.

Paula, G. (1990, March). Expert system diagnoses transmission-line faults. *Electrical World*, pp. S41-S42.

Describes an automatic expert system that uses a mathematical model of a power transmission system for fault diagnosis. The expert system activates upon failure of the transmission system and produces a prioritized list of possible fault locations and their corresponding failure probabilities.

Ray, A. K. (1991, June). Equipment fault diagnosis--a neural network approach. *Computers in Industry*, pp. 169-177.

Describes a system designed for mechanical equipment diagnosis in the steel industry.

Reason, J. (1987, March). Expert systems promise to cut critical machine downtime. *Power*, pp. 17-24.

Discusses prospects for continuous vibration monitoring systems, leading to automatic diagnostic systems. The article also highlights several expert systems in the power industry. `Turbomac' is an expert system for diagnosing vibrations in large turbo machinery, particularly power generating facilities.

`GenAid' is an expert system developed by Westinghouse Electric Corp. for diagnosing hydrogen-cooled electric generators. The purpose of GenAid was to avoid catastrophic failure. See also King, Chianese, and Chow (1988, December).

The Central-Hudson Electric & Gas Corp. developed an expert system for scheduling outages. The purpose of the system was to reduce the number of scheduled outages without compromising equipment integrity. The system schedules outages for preventive maintenance at the first sign of trouble.

`Transformer Oil Gas Analyst' is an expert system for detecting and diagnosing signs of impending transformer failure.

General Electric developed an expert system for turbines. The system is portable, links to a video disk display, and uses voice recognition for form fill-in or multiple choice input.

Rodriguez, G., & River, P. (1986, July). A practical approach to expert systems for safety and diagnostics. *InTech*, pp. 53-57.

Describes an expert system for diagnosis of a 400/200 KV hybrid gas insulated substation of the Laguna Verde Nuclear Power Station in Mexico. Engineers and literature provided information to build fault trees to model loss of current to safety-related control boards. System objectives were the timely diagnosis of abnormal events or transients, and analysis of events leading to, and consequences of, an abnormal situation.

Roth, E. M., Bennett, K. B., & Woods, D. D. (1987). Human interaction with an "intelligent" machine. *International Journal of Man-Machine Studies, 27,* 479-525.

Reports a study investigating technicians using an expert system to troubleshoot an electro-mechanical device. The article documents common problems of `machine expert' problem solving systems. Only technicians who were actively involved in the problem solving process and who performed actions in addition to those requested by the expert system successfully completed the sample tasks. Technicians who responded passively to expert system requests were unable to solve the problems. This study should be read by all those interested in improving human performance through computational support.

Rowan, D. A. (1988, May). AI enhances on-line fault diagnosis. *InTech*, pp. 52-55.

Describes `Fault Analysis Consultant' (Falcon) for on-line fault diagnosis in a commercial chemical plant. Falcon reasons from first principles and heuristic knowledge. Falcon went on-line in 1988.

Rustace, P. (1988, June 9). Knowledge of an expert compressed on computer. *The Engineer*, p. 44.

Discusses monitoring expert system for gas turbine-driven compressor sets.

Save plant know-how with expert systems. (1987, August). *Electrical World,* pp. 54-55.

Discusses expert system to resolve power plant control room alarms.

Schaaf, J. R. (1985, September). Computerization of sewer maintenance scheduling. *Public Works,* pp. 128-129.

`Computerization of Sewer Maintenance Operations' (COSMO) schedules routine cleaning operations. COSMO also tracks performance, debris severity, and maintenance history and uses this information to set cleaning priorities and schedule sewer cleaning. Database system.

Shifrin, C. A. (1985, October 28). Eastern computer system reduces maintenance layovers, staff levels. *Aviation Week & Space Technology*, pp. 40-45.

Describes a computer system that includes computerized work cards to be filled in by maintenance personnel. The system will also produce hard copies of tasks and checks. The work cards contain detailed instructions, warnings, and notes. The system aids in capacity planning through tracking line slippage, schedule constraints, and manpower limitations.

The article also discusses a parts tracking and scheduling system.

Smith, D. J. (1987, May). Diagnostic analysis leads the way in preventive maintenance. *Power Engineering*, pp. 12-19.

Describes `Process Diagnosis System' (PDS) developed by Westinghouse R&D Center and Carnegie Mellon University. PDS diagnoses problems with steam generators and provides recommendations and procedures for fixing the problems. PDS is claimed to cut down on `over-maintenance', but prevent `breakdown maintenance'. The system monitors the condition of an operational plant and analyzes plant data to detect incipient faults and deterioration. PDS uses this information to diagnose faults and predict the duration of safe operation without maintenance. PDS also recommends preventive maintenance tasks to be performed during scheduled down periods.

Smith, D. J. (1989, January). Artificial intelligence--today's new design and diagnostic tool. *Power Engineering*, pp. 26-30.

Overview of AI applications in maintenance. The article describes the EPRI-developed `Gas Turbine Expert System' and a Westinghouse-developed system for on-line valve diagnosis

Smith, D. J. (1989, December). Intelligent computer systems enhance power plant operations. *Power Engineering*, pp. 21-26.

Discusses several expert systems in use in the power industry. The `ESCARTA' system for reducing boiler tube failures has several uses: it permits an engineer to track down a failure mechanism, it provides non-destructive testing procedures, it provides welding procedures, it provides corrective actions for failure repair, and it facilitates training. ESCARTA will show operators the correct procedures for investigating tube failures. It also suggests root causes that could have led to a failure. ESCARTA is pc based.

`Coal Quality Advisor' assesses coal quality. The system helps assess cost and performance aspects of using different coals or coal blends. It is pc based.

`Smart Operator's Aid for Power Plant Optimization' diagnoses causes of heat rate degradation on oil- and gas-fired power plants. The system justifies its diagnosis through logic trees or messages. It also recommends corrective actions.

`TurbinAID', `GenAID', and `ChemAID' make up a suite of expert systems for diagnosis of turbine generators. The systems were developed by Westinghouse Electric Corp. See also King, Chianese, and Chow (1988, December).

Stacklin, C. A. (1990, June). Pairing on-line diagnostics with real-time expert systems. *Power*, pp. 55-58.

Concept paper on using expert systems to reduce unscheduled down time. Discusses fault trees, failure modes and effects analyses, and pattern recognition.

Stein, K. J. (1988, March 14). Expert system technology spurs advances in training, maintenance. *Aviation Week & Space Technology*, pp. 229-233.

Discusses emerging expert system technology in maintenance. The Navy Sea System Command's Integrated Diagnostic Support System (IDSS) collects fault-related data and isolates faults. The system continually builds its knowledge base so that it becomes more efficient with use. IDSS will isolate faults to the microchip level by using fault trees. IDSS uses a touch screen, a flat panel display, and an interactive maintenance tutorial on a video disk. IDSS is expected to aid systems designers in building self-diagnostics in new avionics systems.

The article also describes Flex-MATE for use with the USAF modular automatic test equipment.

Stovicek, D. (1991, February). Cloning knowledge. *Automation*, pp. 46-48.

Discusses General Motors' `Charley' system for vibration analysis of production equipment. Charley is an expert system developed by GM's Advanced Engineering Staff and is named and modeled after a retired vibration analysis expert. Charley contains three modules: 1. a rule-base for vibration analysis, 2. a `vibration signature' database, which contains the vibration curves of the various pieces of equipment, and, 3. a machine database, which contains historical data on each machine. Charley is used for failure diagnosis, preventive maintenance, and training. Charley can be used to answer `what if' questions and explains diagnosis strategies. Runs on a Sun computer. See also "GM unveils..."

Suchman, L. A. (1987). *Plans and situated actions: The problem of human machine communication.*

Discusses human action with respect to circumstantial variability and the difficulties in communicating such variability to a machine. Rigid problem solving on the part of the machine and misinterpretations on the part of the human are some of the obstacles to successful human computer interaction discussed.

Sutton, G. (1986, January). Computers join the maintenance team. *WATER Engineering & Management*, pp. 31-33.

`Maintenance Management System' (MMS) for water and wastewater treatment facilities. MMS tracks organization performance, determines resource utilization and work backlog, and makes personnel and resource utilization projections. It also schedules preventive maintenance. MMS is a database system.

Thandasseri, M. (1986). Expert systems application for TXE4A exchanges. *Electrical Communication, 60(2),* 154-161.

Describes `Advance Maintenance Facility', an expert system for fault identification. Normally the system controls interactions, but it can be `controlled' by an operator. Output is corrective action and post-repair tests.

Toms, M., & Patrick, J. (1987). Some components of fault-finding. *Human Factors, 29(5)*, 587-597.

Research paper on human performance in network fault-finding tasks.

Turpin, B. (1986, March 3). Artificial intelligence: Project needs. *Design News*, pp. 104-114.

Discusses expert system developed by Campbell Soup for diagnosing problems with `cookers'. The system was built to replace a retiring technician with 25 years of experience.

The article also discusses an expert system (Intelligent Machine Prognosticator) developed by Texas Instruments for epitaxial reactor maintenance. See also Kinnucan (1985, November).

Users get expert advice on-site. (1987, March 12). *ENR*, p. 21.

The `Exstra' expert system troubleshoots mechanical equipment failures in compressors, water pumps, and other rotating equipment. Exstra lists possible conclusions with likelihood ratings. It also explains why it asks particular questions. Exstra is VAX based.

Uttley, A. (1985, October 17). Computer `expert' helps find faults. *The Engineer*, p. 76.

Describes expert system shell software.

Vanpelt, H. E., & Ashe, K. L. (1989, April). Radiation exposure reduced with computer-aided maintenance. *Power Engineering*, pp. 40-42.

Describes `Plant Radiological Status' (PRS), a three dimensional computer model of a power generating station and its equipment, developed by Duke Power Co. PRS is claimed to reduce maintenance time and radiation exposure by supporting planning activities. PRS identifies maintenance interference problems (e.g., restricted access) and available work space. PRS also facilitates access and interpretation of radiological conditions in the plant; it identifies hot spots and contaminated areas.

Woods, D. D. & Roth, E. M. (1988). Cognitive engineering: Human problem solving with tools. *Human Factors, 30(4)*, 415-430.

Concept paper which describes the fundamental aspects of cognitive engineering. According to the authors, "Cognitive engineering is an applied cognitive science that draws on the knowledge and techniques of cognitive psychology and related disciplines to provide the foundation for principle-driven design of person-machine systems." (p. 415). Like Roth, Bennett, & Woods (1987), this article should be read by all those interested in supporting human performance through computational support.

Yu, C-C., & Lee, C. (1991). Fault diagnosis based on qualitative/quantitative process knowledge. *AIChE Journal*, *37*, pp. 617-628.

An academic discussion of an approach for combining qualitative and quantitative reasoning in an expert system through fuzzy logic. Aside: Although fuzzy logic is a technique that is often used in artificial intelligence because it doesn't carry the overhead associated with Bayesian or other probability theory based methods, it also lacks the mathematical rigor of the latter methods.