EMERGING TECHNOLOGIES FOR MAINTENANCE JOB AIDS

Charles F. Layton, Ph.D.
Galaxy Scientific Corporation

1.0 INTRODUCTION

Maintenance is fast becoming one of the most frequent applications of computer-based job aiding. Maintenance job aids range from automatic preventive maintenance schedulers, to systems that monitor equipment status and recommend maintenance, 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, including algorithmic approaches for preventive maintenance schedulers to expert systems for fault diagnosis and repair. The technologies employed encompass a range from mini computers to desktop microcomputers linked to video disks. This paper 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. It 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, W. T., Johnson, W. B., Drury, C. G., Taylor, J. C., & Berninger, D., 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.

2.0 SURVEY OF MAINTENANCE JOB AIDS

A survey of academic, industrial, and popular literature revealed a wide variety of approaches to building maintenance job aids. 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.

2.1 HARDWARE EMPLOYED

The following systems exemplify the variety of hardware approaches used for maintenance job aids.

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 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 into 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. During this off-line 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..."). For example, 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.

2.2 METHODS EMPLOYED

The following systems exemplify the range of software methodologies employed in maintenance job aids.

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.)

`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 modeled; thus, `modeled-based reasoning' is often used to describe this approach. 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.

3.0 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.

3.1 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 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 the `Charley' system 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.

3.3 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.

4.0 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 of 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.

5.0 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.

5.1 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.

5.2 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).

5.3 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.

6.0 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.

7.0 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.

7.1 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.

7.2 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 them 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.

FLIGHT PLANNER, an enroute flight planning software testbed, used three levels of computer support which 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 1 depicts the map displays and controls, and Figure 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.

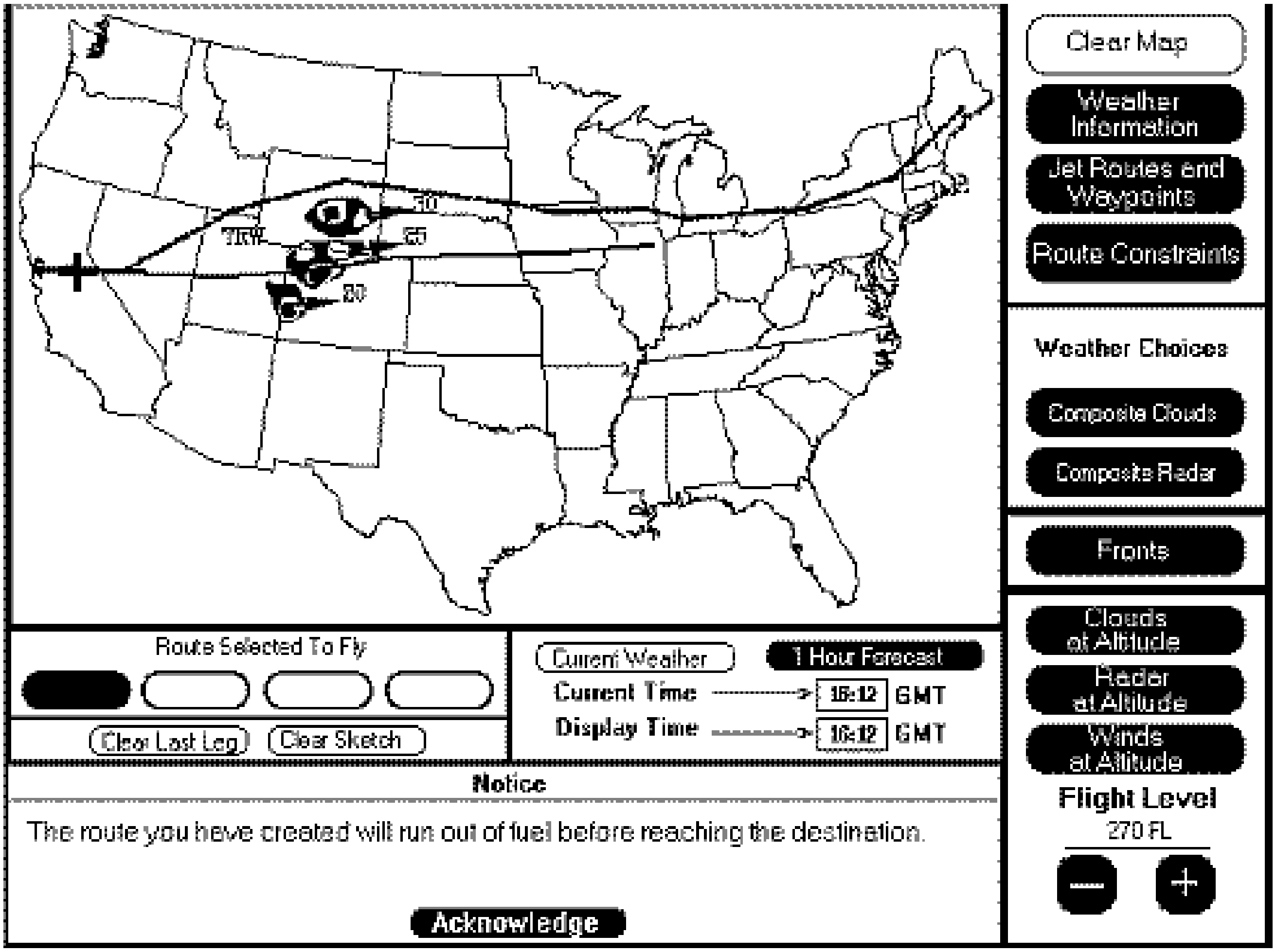

Figure 1 Left Monitor Displays and Controls

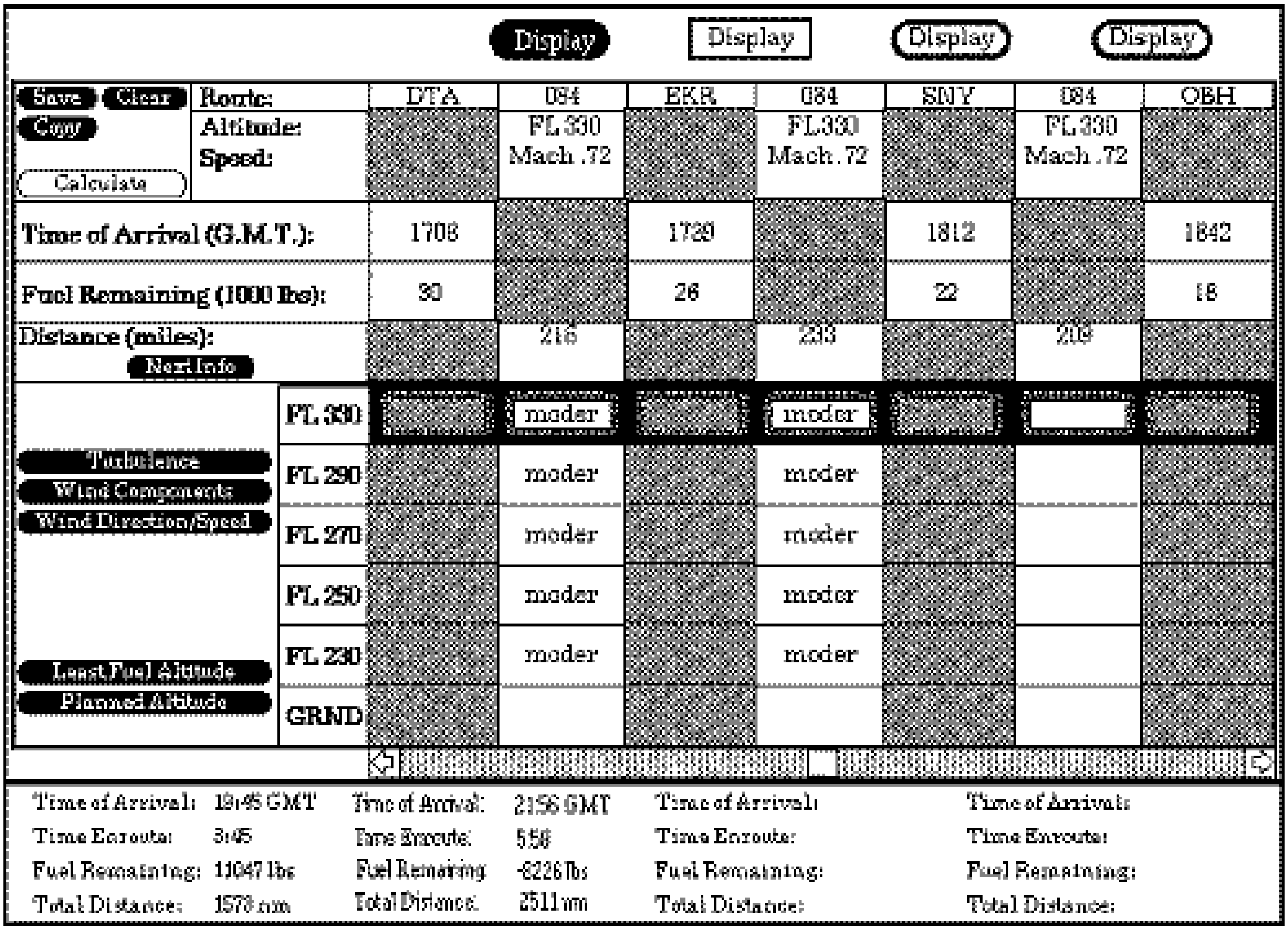

Figure 2 Right Monitor Displays and Controls

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.

7.3 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.

7.4 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.

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.

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.

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.

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.

7.5 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.

7.6 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 of the pump feeding 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)

8.0 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 maintenance job aid was presented.

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