SUCCESS IN TUTORING ELECTRONIC TROUBLESHOOTING

Ellen M. Parker
Air Force Human Resources Laboratory
Manpower and Personnel Division
Brooks AFB, TX 78235-5601

ABSTRACT

Two years ago at this conference, Dr. Sherrie Gott of the Air Force Human Resources Laboratory described an avionics troubleshooting tutor being developed under the the Basic Job Skills Research Program. The tutor, known as Sherlock, is directed at teaching the diagnostic procedures necessary to investigate complex test equipment used to maintain F-15 fighter aircraft. Since Dr. Gott's presentation in 1987, the tutor has undergone field testing at two Air Force F-15 flying wings. The results of the field test showed that after an average of 20 hours on the tutor, the 16 airmen in the experimental group (who averaged 28 months of experience) showed significant performance gains when compared to a control group (having a mean experience level of 37 months) who continued participating in the existing on-the-job training program. Troubleshooting performance of the tutored group approached the level of proficiency of highly experienced airmen (averaging approximately 114 months of experience), and these performance gains were confirmed in delayed testing six months following the intervention. The tutor is currently undergoing a hardware and software conversion from a Xerox Lisp environment to a PC-based environment using an object-oriented programming language. This paper summarizes the results of the successful field test and focusses on (a) the instructional features that contributed to Sherlock's success, and (b) the implementation of these features in the PC-based version of the avionics troubleshooting tutor.

INTRODUCTION

In developing the avionics troubleshooting tutor to be described in this paper, the Basic Job Skills Program attempted to address several fundamental problems that the Air Force maintenance community faces with respect to the training of mainten-ance technicians. First, while the complexity of the systems to be maintained is increasing with advances in aerospace technology, there has been no corresponding increase in the time available to new trainees to learn about these systems. As a result, the time needed to acquire the knowledge necessary to perform these jobs increases and the Air Force has received fewer of the benefits of its training by the time maintenance personnel leave the Air Force.

One response to the increase in the technical complexity of these jobs has been to provide technicicans with procedura-lized job aids and so-called 'smart' machines equipped with self-diagnostic capabilities. The rationale supporting this response is that in providing tech-nicians with cook-book procedures for dealing with maintenance problems they might encounter, together with machines that diagnose their own faults, one can reduce the knowledge and skill required of the human technician and still main-tain the productivity of the work force. Unfortunately, the adequacy of procedura-lized job aids is limited by the fact that, given the complexity of current aircraft systems, even the best designers are unable to anticipate every conceiv-able fault or fault combination that their system might develop. There are also limits to the diagnostic capabili-ties of automated systems. For example, Gott (1987) cited a 65% hit rate for the diagnostics of some systems on the B1B. Thus, there is still a clear need for human expertise to pick up where procedu-ral aids and automated diagnostics leave off. A related consequence is that re-liance on such aids gives technicians a false sense of security and undermines the development of the expertise that will invariably be required when the technician is confronted with a novel set of conditions for which the proper repair procedures have not been prespecified.

A final dimension of the maintenance training has to do with the fact that the

first priority in the shops where technicians receive their on-the-job training is rarely to train new technicians, but to keep planes flying. This means turning out units that come into the shop for repair as quickly as possible. In order to meet this goal and to keep inexperienced personnel from breaking expensive equipment, it is often only the most experienced technicians who work on the more difficult problems. Thus, trainees are denied important learning opportunities where practice at solving difficult diagnostic problems would promote their understanding of the task and the system they are working with.

DEVELOPMENT AND EVALUATION OF AN AVIONICS TROUBLESHOOTING TUTOR

In order to ameliorate these effects, the avionics troubleshooting tutor, Sherlock, was designed to provide trainees with the type of troubleshooting practice that would decrease both the total reliance of novice technicians on automated diagnostics and proceduralized job aids, as well as the amount of time required to acheive proficiency in the task of maintaining aircraft systems. The design was based on analyses of expert troubleshooting performance (Gitomer, 1984, 1988; Glaser et al., 1985; Gott, Bennett, and Gillett, 1986) which identified three cognitive components of their expertise: the knowledge underlying experts' use of troubleshooting procedures such as tracing electrical signals using schematics and taking measurements of the signals; the strategic knowledge underlying decisions regarding appropriate actions to take given multiple alternatives; and the declarative knowledge of the system itself which allows experts to accurately represent the problem and thereby construct and constrain the problem space. Sherlock incorporates a series of 34 troubleshooting scenarios that are designed to foster these multiple types of expert knowledge. The scenarios are presented to students in an ordered sequence. This sequence was informed by the examination of novice weaknesses in the cognitive task analysis, and was designed to foster increasingly sophisticated models of the test equipment and the troubleshooting task.

Sherlock was evaluated in a controlled experiment at two Air Force F-15 flying wings (Nichols, Pokorny, Jones, Gott, and Alley, in preparation; Gott, 1989). A verbal troubleshooting test was used to identify 32 avionics technicians who had either beginning or intermediate troubleshooting skills (see Nichols, et al. for a complete description of the verbal troubleshooting task). On the basis of their performance, subjects were ranked within testing site and matched pairs

were established. One member of each matched pair was then randomly assigned to either the experimental or control group such that half the subjects at each testing site were assigned to each group. Subjects' scores on the verbal troubleshooting task provided a baseline measure against which performance gains could be measured post-experimentally. The pretest scores revealed no significant differences between groups in performance on either the verbal troubleshooting problems that were administered at both bases or on a number of other indicators that were used to corroborate the equality of groups prior to the intervention (see Nichols, et al. for a complete description of these measures).

The experimental subjects received an average of 20 hours on Sherlock over the course of approximately three weeks while the control subjects continued their on-the-job training. Parallel forms of pretest measures were then readministered as posttests by researchers who were blind with respect to individual subjects' participation in either the experimental or control group. Figure 1 shows differences in pre- and post-test performance on the verbal troubleshooting task for the two groups. An independent samples t-test revealed no significant differences between mean pre-test scores of 53.40 for the control group and 56.93 for the tutor group (t(30)=0.38, p>.5, two tailed). Post-test performance, however, differed significantly (F(1,29)= 15.62, p<.01), with tutored subjects obtaining a mean score approximately 20 points higher than that of control subjects. In order to get some idea of what this performance gain translates to in terms of increased experience, a group of skilled airmen with an average of 114 months of experience in this career field was tested on the verbal troubleshooting task. Their mean score is plotted in the upper left-hand corner of Figure 1, and is quite similar to that of the tutored group who had an average of only 28 months of experience. When experimental and control subjects were retested 5 to 6 months after the experiment had been conducted, the tutor's effect persisted with tutored subjects achieving a mean score approximately 15 points higher than that of the control group. When compared with their immediate posttest performance, the slight performance decrement of the tutored group on the delayed posttest was not statistically significant.

The success of the Sherlock field test has resulted in high-level support for the BJS program from within Tactical Air Command which employs the maintenance personnel whose training Sherlock targets. In order to get the tutor into Air Force maintenance work places, Sher-

lock is currently undergoing a hardware and software conversion which will allow the system to be delivered on standard PC hardware that is available in maintenance work centers. This conversion is being carried out at the University of Pittsburgh Learning Research and Development Center by researchers responsible for the original development of Sherlock. In addition to the need for delivering Sherlock on standard Air Force hardware, decisions regarding Sherlock's conversion have been driven by three primary concerns: first, the instructional features that led to the tutor's success must be better understood and retained; secondly, the tutor's limitations must be explicated and reduced; and finally, the resultant tutor courseware must be maintainable by Air Force personnel.

INSTRUCTIONAL FEATURES OF THE AVIONICS TROUBLESHOOTING TUTOR: TROUBLESHOOTING PRACTICE IN A SIMULATED, SUPPORTED WORK ENVIORNMENT

The instructional features of Sherlock that appear to be responsible for the dramatic learning gains are associated with the simulated, supported practice environment that the tutor provides. Specifically, opportunities for realistic practice, feedback to foster the development of a mental model of an electronic test, menus that support the development of goal-oriented activity, and multiple levels of hints from Sherlock's coach are of particular interest.

One of Sherlock's most important instructional features is that it provides students with the opportunity to practice solving realistic troubleshooting problems in a simulated but supported work environment. Figure 2 shows the tutor display as it appears to the student upon presentation of a troubleshooting problem. The context of the problem is established by presentation to the student of a scenario that technicians might encounter on the job. The problem is thus presented in much the same way that a real problem would present itself in the shop. The work environment of the shop is also represented in the form of a simulated test station, a unit from the jet that is being tested (referred to as a line replaceable unit or LRU), and a test package connecting the LRU to the test station. The simulated dimensions of the equipment are primarily the external controls of test station drawers rather than their internal functional behavior. Front panels of test station drawers were graphically simulated to appear as similar to the real work environment as possible, and indicators and controls were functionally simulated to allow manipulation by the student for the purpose of performing tests and taking measurements. Within the test station, measurements are taken by selecting test points on schematic diagrams displayed on Sherlock's screen. Measurement values have been prespecified, however, and do not result from an underlying deep simulation of the device (i.e., test equipment and LRU).

In most of Sherlock's problems, as in the real shop environment, a corrective action or 'fix' called out by the technical orders for a failed test step rarely fixes the problem. It is at this point then that students must begin to think on their own to develop a plan for isolating the fault. This requires relating the failed test to a mental model of the system as it was presumed to be functioning at the time of the fail. This envisioning process involves representing components of the system that were active during the test, and the flow of information through these components. Figure 3 illustrates an abstract model of an electronic test which can be used to characterize any circuit path that the student might have to investigate. A stimulus signal is generated by one of the drawers in the test station, and sent to a routing device which routes the signal through the test package and the LRU. The LRU responds to the input signal and produces an output which is sent back to the test station and routed to a measurement device (Lesgold, Lajoie, Bunzo, and Eggan, 1988). In relating this abstraction to a particular test, the student is encouraged to identify the active circuit path for that test. The model of the test thus provides a structure for the organization of the student's declarative knowledge of the system and constrains the search for the fault.

The tutor is also directed at the development of goal structures for investigating the equipment, procedural knowledge of specific troubleshooting actions, and additional strategic knowledge required to inform decision making during problem solving (Gott, 1989). Sherlock's action menu, shown at the right-hand side of the display reproduced in Figure 2, allows students to choose which area of the equipment they want to investigate, and to select the procedures for doing so. Some of these menu selections have additional choices embedded within them representing further decisions that the technician must make in pursuing a particular solution path. The menus serve to structure the problem-solving process and facilitate the apprentice's development of a conceptual model of the task. Thus, for example, in testing an LRU that has come in from the flight line, the student must access the technical order that describes the test procedures for that particular LRU, set up the drawers as

instructed for each test on the LRU
(e.g., wiring integrity tests, power
short tests, resistance tests, etc.), and
run and interpret each test. If a test
fails, the technical order might call out
a suggested fix for the fault, and the
student is encouraged to try that fix
before investigating other components as
the cause of the failed test. Other
procedural choices represented in Sher-
lock's action menus include selection of
test points, selection of components to
be replaced, swapping suspected bad com-
ponents, checking connections, etc.
Sherlock thereby provides a simulated
learning and practice environment so that
technicians can exercise the skills they
must use in the real work environment.
Moreover, Sherlock embodies a coach or
master technician to foster apprentice-
ship learning with feedback and general
problem solving assistance.

Sherlock's coach offers external support
in the form of hints that are provided
when the student asks for help. The
hints, like the action menu choices, are
tied to the goal structure of fault iso-
lation tasks, and vary according to type
and level of explicitness. Hint type is
related to the student's current trouble-
shooting activity and specifies, for
example, where to take a measurement or
how to interpret a measurement already
taken. The explicitness of the hint is
determined by the student who can access
up to five levels of increasingly direc-
tive hints, from a simple recap of past
plans and actions, to detailed informa-
tion concerning how to perform the next
suggested action. Unsolicited interven-
tion from the coach can also occur under
certain circumstances, for example, if
the student fails to turn off a hazardous
voltage prior to extending a circuit
card, or investigates a piece of equip-
ment that was not being used when the
test failed. Sherlock's hints are thus
adaptive in the sense that hints received
are dependent on the individual student's
activity at the time the hint is ac-
cessed, and the desired level of assist-
ance as indicated by the specificity of
the hint requested.

Sherlock's instructional limitations re-
sult primarily from the fact that the
tutor's curriculum is to a large extent
prespecified. The problems presented to
students and their sequence is the same
for all students, regardless of their
individual strengths and weaknesses. Al-
though the tutor evaluates students'
problem solutions and highlights their
strengths and weaknesses in post-problem
feedback, this diagnostic capability is
not exploited to provide problems that
are particularly adapted to the indivi-
dual student's current level of skill.
This lack of adaptiveness exists because

the tutor does not possess the capability
of generating new problems on line in the
course of tutoring. Further, on-line
diagnosis of students' troubleshooting is
not robust enough to determine the appro-
priate type and level of hint to provide
when a student asks for help. While the
presentation of hints is adaptive in the
sense described earlier, the hints them-
selves have been prespecified and the
principles that determine hint content
and guide Sherlock's decisions to inter-
vene are not as yet clearly established.
In the next version of the tutor, simula-
tion will be deeper in the sense that a
set of circuits will be functionally
simulated and the electronic tests per-
formed on these circuits will be mo-
delled. This simulation will provide the
basis for improved student modelling and
diagnosis, on-line problem generation,
and more principled explanations and
student feedback (see following section
for a more complete discussion of how
these improvements will be implemented).

THE AVIONICS TROUBLESHOOTING TUTOR II

The next generation of Sherlock is pre-
sently under development, with the con-
cerns described above providing the foci
for the effort. The goals include deli-
very of instruction on accessible, cost-
effective hardware, simplification of
tutor development and maintenance by Air
Force personnel, and increased adaptive-
ness in instruction, including improved
student diagnosis and on-line problem
generation capability.

Sherlock was originally implemented in
the Xerox Lisp environment in order to
take advantage of its large internal
memory capacity and superior graphics
capabilities. The idea was to first test
the validity of the cognitive models and
theory underlying Sherlock's design uti-
lizing optimal computer hardware. Now
that the theoretical and empirical bases
of Sherlock have been tested and suppor-
ted, we must consider ways of delivering
the tutor on a scaled-down system without
sacrificing essential performance charac-
teristics of more powerful machines. The
basic configuration of the Avionics
Troubleshooting Tutor II is depicted in
Figure 4. The system consists of an
80386-based PC with one MB of internal
memory and two to three MB of expansion
memory. The PC is connected, via an RS-
232 cable, to a video disc player which
stores video images to be displayed on a
20-inch multiscan, high-resolution moni-
tor. The PC is equipped with VGA graphics
and a superimposer board for overlaying
computer graphics on video images.

The use of video in displaying the work
environment provides several advantages
over computer graphics. First, by using

video images of the real test equipment, Sherlock's feature of providing a realistic work environment is retained, and in fact, enhanced with concrete visual representations of actual physical equipment. Figure 5 shows the front panel of one of the test station drawers in the original Sherlock. The time required to develop such detailed graphics and all possible configurations of each front panel, not to mention their storage requirements, represents a significant investment of resources to achieve work environment realism in Sherlock I. That investment will be significantly reduced via the use of video in Sherlock II. In that version of the tutor, computer graphics will be used almost exclusively in the menus, with a resultant savings in development time and storage. Second, because the Air Force maintenance community currently uses interactive video in developing (and delivering) its maintenance training, instructional designers who will ultimately maintain the tutor are already familiar with the technology.

The converted tutor is being developed in the Smalltalk V286 software environment which will allow significant savings in development time and facilitate the implementation of more adaptive instruction in the form of on-line hint and problem generation. Recall that the converted tutor will employ simulated circuits. The object-oriented environment provided by Smalltalk was chosen since it implements sophisticated class structures with asynchronous messaging between objects, thereby allowing for the simulation of complex systems. The environment also reduces development time because the object class structure defined by the programmer determines the properties of objects within a class and the operations that can be applied to them. Put another way, objects inherit the properties and operations (or methods) of their class which are defined only once for the entire class rather than for each object within the class. The reduction in development time thus results from the ability to, in effect, use a given piece of code for multiple purposes.

The implementation of a class structure is illustrated by the simulated circuits being developed for Sherlock II, and the electronic tests which operate on the circuit. Each instance of a test involves four elements: a signal source, an LRU (the unit being tested), a measurement device, and a circuit path. Although different tests may use different circuit paths, stimulus sources, etc., all instances of each element have certain behaviors in common. For instance, a broken wire in any circuit path will, in general, cause an ohms measurement to indicate infinite resistance. If, in a particular circuit, the wire was shorted to another wire, the reading might be different. It is only under these unusual types of conditions that additional code must be written to override the behavior that defines circuits in general. Thus, rather than coding each circuit to be used in the tests independently, all circuits will share code that defines their common behaviors. The ability to capture the general properties of objects will provide the basis for rule-based problem generation and hint generation in Sherlock II. Given that problems and hints can be created by rule, then they can be generated during the course of the tutoring session in a way that is responsive to the individual's troubleshooting strengths and weaknesses, thus providing more adaptive instruction.

The object-oriented programming environment also promotes maintainability of the tutor because it lends itself to modularization. Modular code makes the structure of the program clearer, thus facilitating modifications by programmers who were not involved in the tutor's original development. Modules that do not require modification for new versions of the tutor or for other tutors being developed for different maintenance job specialties can also be easily transported. The BJS Program is currently conducting a training needs assessment to determine the type of programming expertise required for maintenance of intelligent tutors developed in the object-oriented languages so that this task can be performed by Air Force personnel.

CONCLUSIONS

In addressing the needs of the Air Force maintenance community, the Basic Job Skills Program has benefitted from methodological and theoretical advances in cognitive science. These benefits are reflected in, for instance, the cognitive task analysis procedure which was used to inform Sherlock's design (Gott, 1987) and the increasingly comprehensive models of troubleshooting performance that the results of these analyses yield. To the extent that the cognitive approach to Sherlock's design contributed to the tutor's effectiveness, then an important future goal for the BJS Program will be to make this technology available to nonscientists in the Air Force who are responsible for instructional design and maintenance of educational courseware. Steps toward this goal include the development of maintainable software that is compatible with standard hardware, and the attempt to gain a better understanding of the instructional approach required in teaching a complex skill like troubleshooting.

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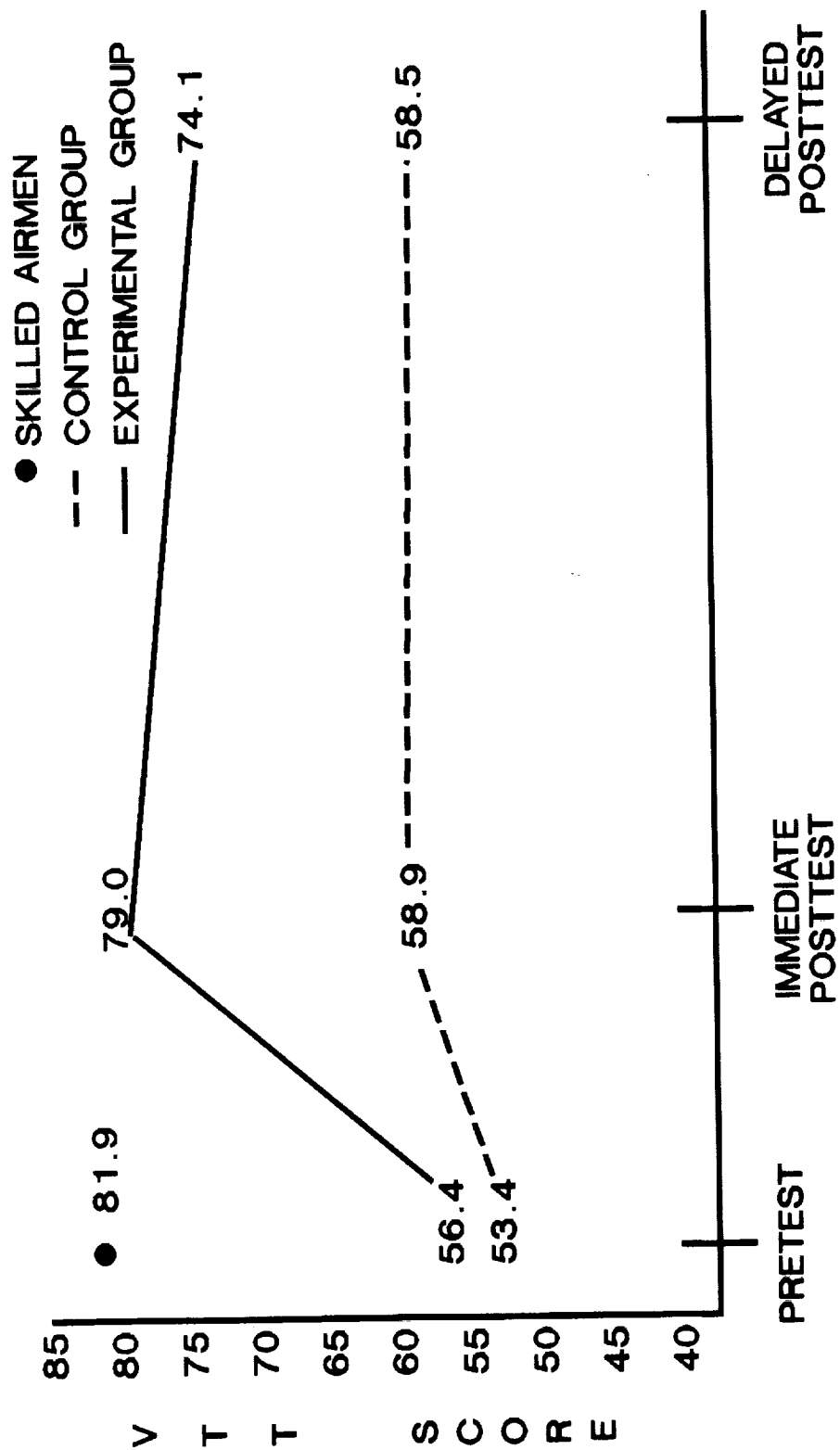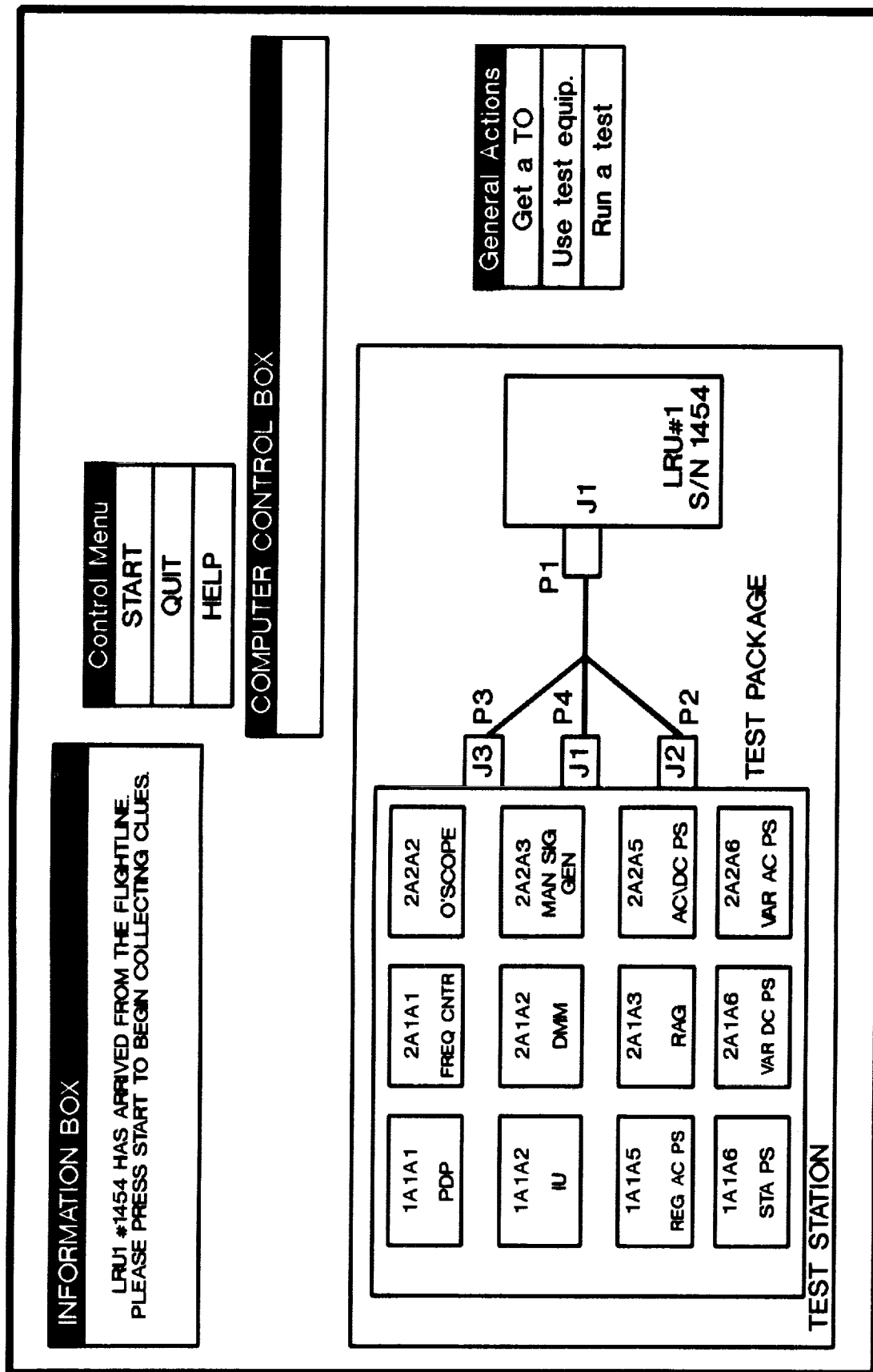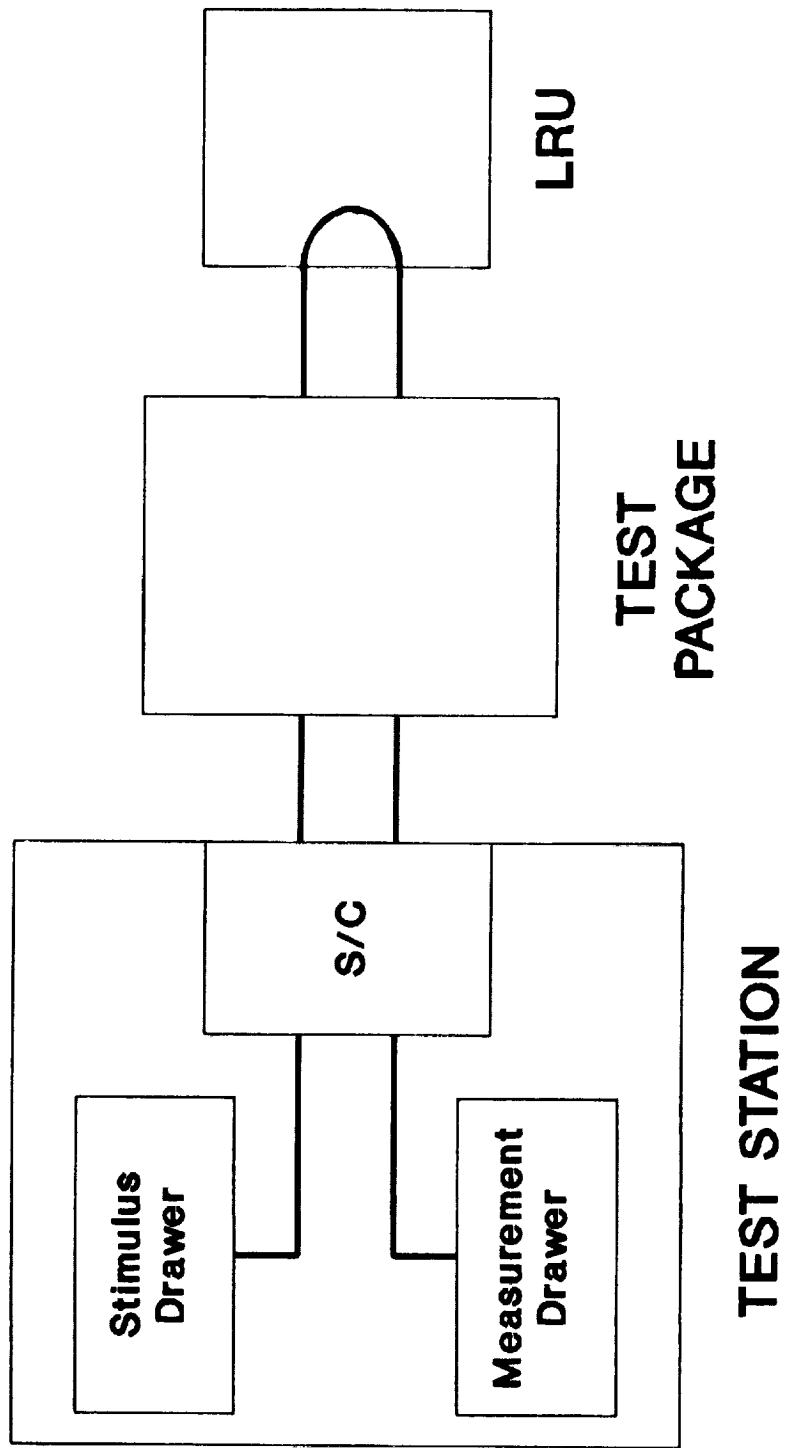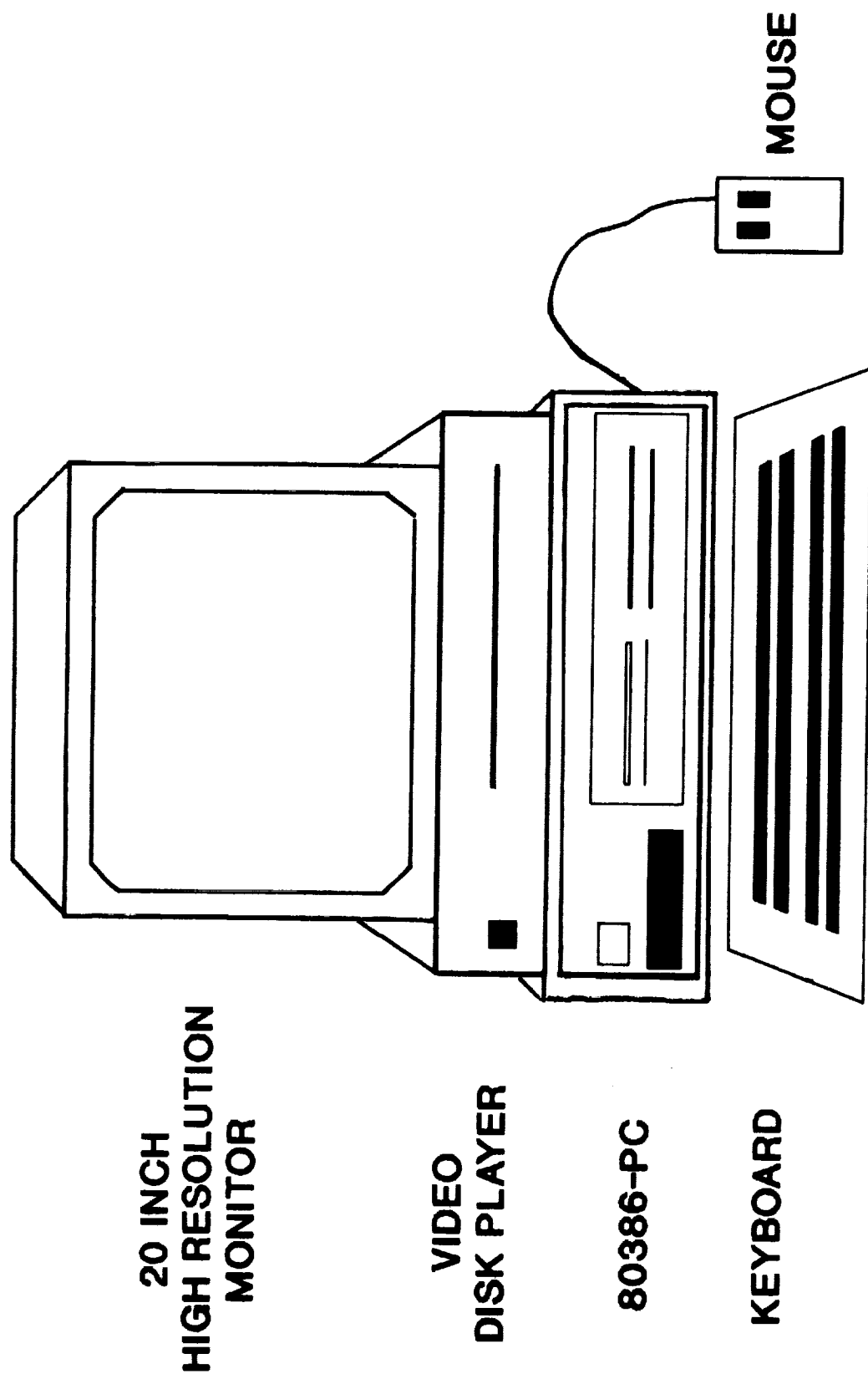
FIG. 1. RESULTS OF FIELD TEST

INFORMATION BOX

LRU1 #1454 HAS ARRIVED FROM THE FLIGHTLINE. PLEASE PRESS START TO BEGIN COLLECTING CLUES.

Control Menu
START
QUIT
HELP

COMPUTER CONTROL BOX

General Actions
Get a TO
Use test equip.
Run a test

LRU#1
S/N 1454

J1
P1
P3
P4
P2
J3
J1
J2

TEST PACKAGE

1A1A1 PDP	2A1A1 FREQ CNTR	2A2A2 O'SCOPE
1A1A2 IU	2A1A2 DMM	2A2A3 MAN SIG GEN
1A1A5 REG AC PS	2A1A3 RAG	2A2A5 AC\DC PS
1A1A6 STA PS	2A1A6 VAR DC PS	2A2A6 VAR AC PS

TEST STATION

FIG. 2. WORK ENVIRONMENT DISPLAY

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FIG. 3. AVIONICS EQUIPMENT CONFIGURATION
(SIGNAL PATH)

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MOUSE

20 INCH
HIGH RESOLUTION
MONITOR

VIDEO
DISK PLAYER

80386-PC

KEYBOARD

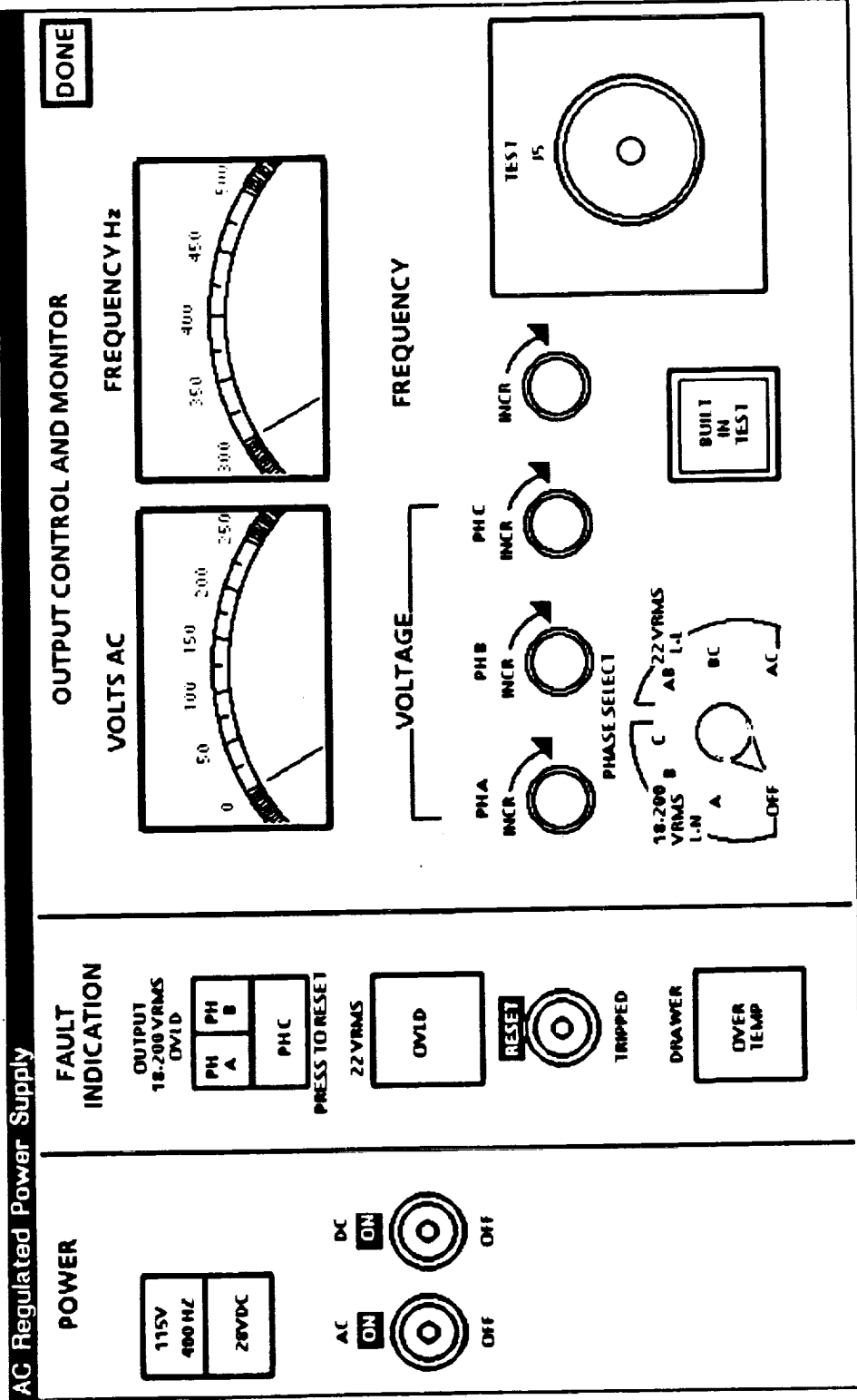FIG. 4. CONFIGURATION OF
AVIONICS TROUBLESHOOTING TUTOR II

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FIG. 5. FRONT PANEL DISPLAY OF A TEST STATION DRAWER IN SHERLOCK

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