# DEVELOPING TROUBLESHOOTING EXPERTISE THROUGH INTELLIGENT COMPUTER - ASSISTED INSTRUCTION

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## ABSTRACT

The present research and development study explores new techniques for developing the aircraft troubleshooting generalists demanded for both turn-of-the-century combat effectiveness and peacetime cost-control. An economical, computer-based apprenticeship program is being developed that uses artificial intelligence to provide the benefits of individual tutoring and expert-guided practice of newly developing skills. The computer realistically depicts both aircraft equipment and flightline maintenance aids during troubleshooting simulations to improve transfer of training from the classroom to the job. Rigorous front-end analyses guided the instructional design. These analyses revealed commonalities in equipment and troubleshooting procedures across different aircraft systems, which form the focus of the skill generalization training. Likewise, distinguishing characteristics of expert troubleshooters were identified and targeted as training outcomes. Finally, a theoretical framework has been developed to guide further efforts for improving generalized maintenance problem solving skills.

## INTRODUCTION

Aircraft readiness requires highly skilled maintenance technicians to efficiently diagnose failures. Unfortunately, relatively little formal military training is devoted to the development of troubleshooting skills. Rather, technicians must largely learn troubleshooting techniques on their own through trial-and-error attempts to solve aircraft problems they encounter in the field. As a result, maintenance problem solving skills develop slowly, with few technicians ever becoming expert diagnosticians.

The work described here is an ongoing research and development effort to improve troubleshooting by jointly applying psychological science and computer technology to the development of a new, more effective and efficient type of training program. Although the magnitude of the problem precludes any quick and easy solution, some valuable findings have already been obtained as intermediate outcomes of this long-term investigation. This paper will describe the principal facets of the problem being attacked and outline our objectives and the approach used to achieve them. The current status of the program, its findings, and its future direction will be discussed.

### Troubleshooting Skill Generalization

The little formal troubleshooting training that now exists is highly specialized, resulting in restricted troubleshooting capabilities among novice technicians. Instruction focuses on one piece of equipment at a time, not demonstrating how similar problem solving techniques could apply to related aircraft subsystems/components. Consequently, once in the field, students can troubleshoot only the narrow range of faults they were specifically taught until years of on-the-job training (OJT) and trial-and-error experience provide sufficient practice on a large enough variety of problems to broaden their diagnostic capabilities. Furthermore, by failing to point out similarities in techniques used to isolate related equipment faults, current training misses opportunities to reduce instructional time by building on what students have already learned.

New training techniques must be found to speed development of competent maintenance generalists. Such personnel will be needed to meet military requirements for weapon system survivability, mobility, and operations in the harsh environments of turn-of-the-century warfare.(1) In such combat scenarios, rapid repair of failed aircraft will depend on efficient, accurate fault isolation by small, broadly skilled maintenance teams which can quickly relocate among austere aircraft sites. Expanded troubleshooting skills are also needed in peacetime to promote more efficiency through fewer maintenance specialty codes.(2)

### Realism and Practice Needs

Besides more emphasis on troubleshooting generalization, improved training effectiveness and efficiency require new, cost-effective methods for increasing realism and practice opportunities. Currently, small amounts of supervised OJT are provided to novice maintenance personnel, but these opportunities are diminishing as aircraft become more sophisticated, expensive, and too vital to national security to be set aside for lengthy training periods.

Because of reduced access to aircraft, training now relies largely on lectures accompanied by instructor-led demonstrations on side-panel training devices. However, students have difficulty transferring what is learned through these abstract teaching methods to the actual aircraft, which looks quite different from what is seen in the classroom. Furthermore, instructors in the field point out that most existing training devices are quite restricted in the number of troubleshooting scenarios they can demonstrate. As a result, novice flightline technicians have had limited exposure to only a small fraction of the failures they must diagnose.

Another shortcoming of current group troubleshooting demonstrations, even when provided on actual aircraft equipment, is the lack of hands-on experience they provide. Problem solving investigations in a number of content domains, including equipment diagnosis, have shown that expertise develops largely through extensive solution practice under a variety of problem conditions. Unless training promotes student exploration of diagnostic strategies and offers realistic, intensive practice with troubleshooting techniques, most aircraft technicians will remain relatively unskilled maintenance problem solvers.

## OBJECTIVES

In response to the troubleshooting needs which have been described, we are investigating instructional techniques and content that speed the development of skilled troubleshooting generalists and that readily transfer *diagnostic skills/knowledge from the classroom to the* flightline. Because our focus is turn-of-the-century aircraft maintenance, this training is intended to prepare students for mission scenarios anticipated for that time frame. Consequently, we are replacing some of the rote memorization of traditional training with widely applicable problem solving strategies that capitalize on emerging electronic diagnostic aids and automated technical orders. Students will learn how *to use these aids as extensions of their own problem solving* abilities to efficiently isolate a wide range of aircraft faults.

## APPROACH

To achieve our objectives, we are joining scientific research on *human thinking*, or *cognitive psychology, with* artificial intelligence (AI), which allows computers to perform in ways once possible only for human instructors. As illustrated in Figure 1, this marriage of science and technology produces a new type of apprenticeship program that responds to the diverse backgrounds of student technicians and their needs for realistic, generalizable instruction. This program uses computer-assisted instruction (CAI) enhanced with AI, or intelligent computer-assisted instruction (ICAI), to provide individualized tutorials and a wealth of troubleshooting simulations for practice of new skills.

### Task Analyses and Cognitive Models

Figure 1 shows that the training content is derived from the knowledge and skills used by human troubleshooting experts in the field to ensure the effectiveness and job relevance of what is taught. We are now inputting this knowledge base into the computer with direct assistance from former Air Force NCOs, including crew chiefs. These individuals have had extensive aircraft troubleshooting experience and are now pursuing aircraft supportability careers as civilians. They have trained technicians and can thus offer insights into student entering skills and needs, in addition to providing information about expert approaches to maintenance problem solving. Further prescriptions for good troubleshooting are obtained by consulting rigorous fault

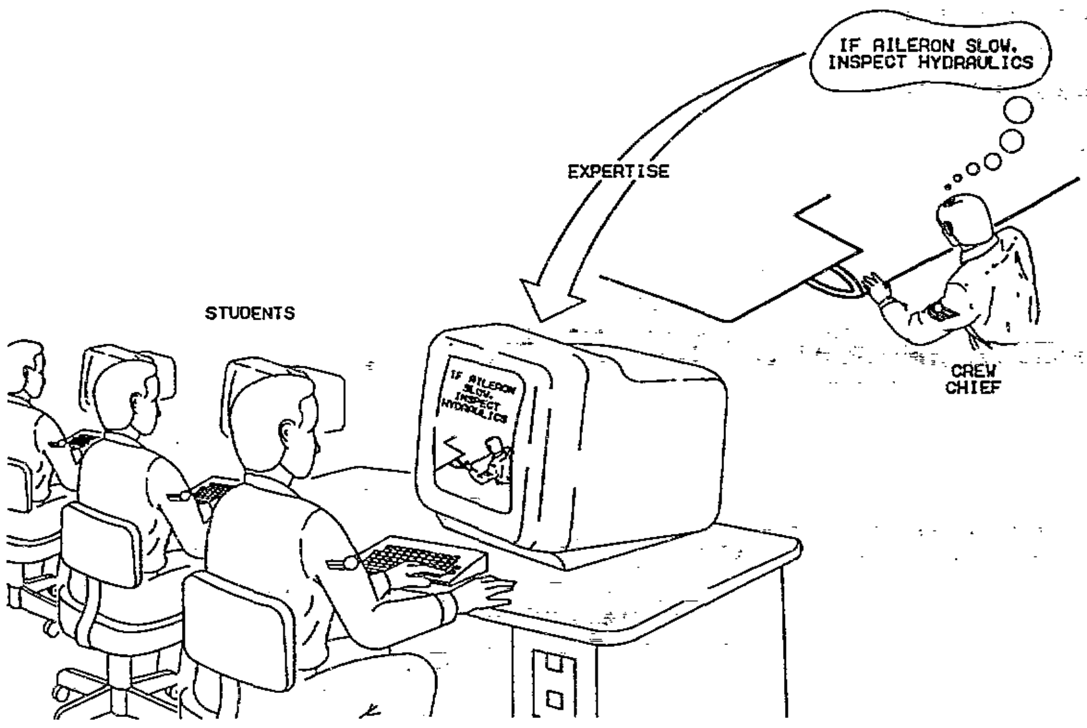


Figure 1. Computer-assisted apprenticeships based on expert knowledge

*reporting manual/fault isolation manual (FRM/FIM)* documentation developed for the Air Force to aid the fault isolation process. The resulting knowledge base in the ICAI system allows each student to effectively have the benefit of a master tutor-technician to introduce troubleshooting techniques and coach their use during simulations, much like a good crew chief might do during OJT.

Our cognitive task analyses of troubleshooting have revealed knowledge and processes needed to accurately and rapidly isolate system failures and have highlighted shared solution components of different problem solving tasks. These shared solution components form the bases for skill generalization and, as such, are the targets of our training for broader troubleshooting capabilities.

The cognitive task analyses have also enabled us to formulate strategies to reduce the time needed to acquire a given level of troubleshooting expertise, thus improving the cost-effectiveness of training. By revealing shared solution components or related knowledge requirements for different troubleshooting tasks, these analyses suggest places in the program to rapidly teach new skills by analogy with tasks already mastered and understood by the student.

Another technique being pursued for improved training economy is to contrast cognitive models of student and expert troubleshooters to pinpoint gaps in student knowledge which must be bridged by training. This allows training to be directed precisely where deficiencies exist and not where proficiency has already been established. Student modeling is accomplished through the AI capabilities of our system as the student interacts with troubleshooting training simulations. The computer's expert system automatically compares the student's solution processes with its own and intervenes with coaching when the student persists in unproductive activities (e.g., unnecessary equipment tests).

Besides using AI to provide equipment simulations and guide student interactions with them, we are now preparing AI-based tutorials to introduce and explain concepts and techniques that improve troubleshooting performance during the simulations and, ultimately, on the job. Because this information is being organized into a knowledge base of interrelated facts, the AI system will be able to respond to spontaneous student requests for further information or elaboration during the tutorials (e.g., upon request, the computer could provide more examples of faults to which a particular diagnostic strategy applies). This approach makes ICAI tutorials more natural, informative, and efficient than what could be accomplished with conventional CAI.

## Realism and Transfer of Training

Student transition from the classroom to the actual aircraft is eased by using high-resolution computer images of aircraft components during tutorials. A digitizing image scanner transfers aircraft photographs to the screen of the computer, reducing graphics creation work. We are also investigating the feasibility and benefits of connecting an interactive videodisc (IVD) player to the AI workstation to provide even more realistic aircraft depictions with the addition of color, motion, and sound. Although conventional CAI software commonly provides simple commands for easy program control of IVD players, off-the-shelf AI software currently lacks such utilities. They are, however, in laboratory development, and we expect to be able to utilize them in the near future.

As shown in Figure 2, besides photographic images, aircraft schematics are displayed on the computer screen during simulated troubleshooting exercises, much like they would be used as a resource on the flightline. Students interacting with these schematics can request tests and replacements of various parts as they isolate faults.

These simulations are being developed with the aid of the System Knowledge Amplifier (SKAMP) AI software package that recently became commercially available. Originally

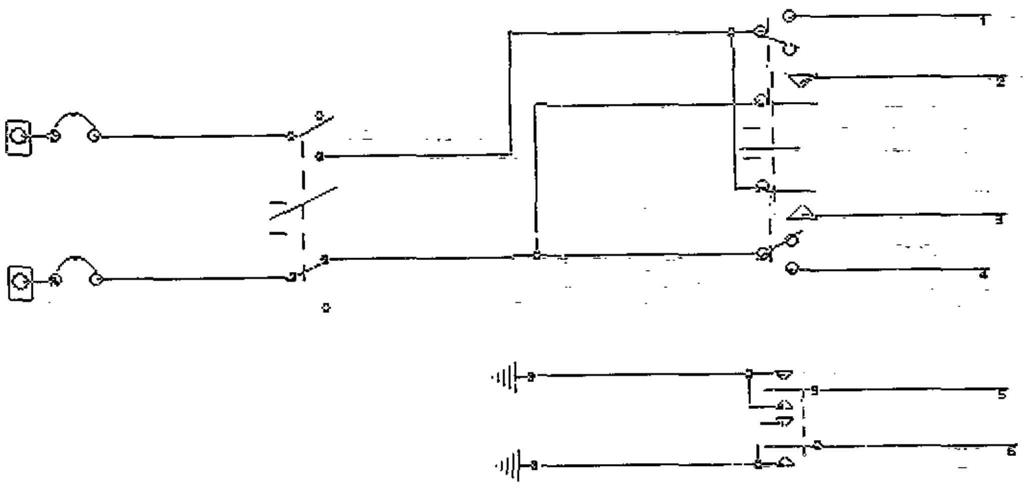


Figure 2. Scene 1 of aileron trim simulation

developed under Navy contract, it allows instructional developers to build simulations by creating graphic/schematic images of equipment items, specifying their rules of operation (including failures), and connecting the equipment images on the screen of the computer, all without knowledge of a programming language. This package possesses a built-in, generic, troubleshooting expert system, which has a firm empirical basis, being derived from over 600 human troubleshooting episodes. The expert system accomplishes the earlier discussed coaching and modeling tasks as students work through simulated troubleshooting exercises. The planned number and variety of simulations will be large enough to provide students, within a relatively short training period, troubleshooting experience equivalent to what would take years to accumulate on the job.

## PROGRESS

Although this investigation is still ongoing, it has already clarified some important issues in troubleshooting training and produced some interesting results. A training context decision that had to be made early in the study will be discussed first. While its outcome is not offered as the only viable one, the scientific and practical criteria used to reach that decision are valid for a variety of programs on troubleshooting generalization and, as such, may be instructive for other researchers. The findings to date of the study, especially those based on the cognitive task analyses, will then be presented as inputs to a theory of problem solving generalization with direct application to our troubleshooting training program.

### Training Context

In conducting the front-end analyses, one of the first tasks was to select a good equipment context in which to teach troubleshooting. Different types of equipment were considered with respect to their potentials for furthering scientific knowledge about problem solving, learning, and instruction and for their relevance to Department of Defense (DoD) needs. Because this study focuses on troubleshooting generalization, special attention was paid to systems comprised of equipment similar to that found in the same system of a different aircraft model. We also considered the likelihood of a particular system remaining in service during the turn-of-the-century maintenance scenarios of interest to this study to ensure the long-term relevance of our findings.

As a result of this analysis, the flight control system was chosen as the study's initial focus. Discussions with engineering, training, and field service personnel within our organization, as well as with DoD personnel, suggested that this system offers rich potential for diagnostic skill generalization. Likewise, flight controls is a problem solving context that has not been well studied in the past. Most troubleshooting training investigations to this point have used either relatively simple, artificial, laboratory problems or have focused on electronic systems, especially avionics. In contrast, military aircraft flight control systems are quite complex, and are usually comprised of mechanical, hydraulic, and electrical components, providing a basis for comparing, and perhaps generalizing, results from studies in other domains. Such cross-domain comparisons could prove especially interesting for DoD aircraft maintenance, since they provide a check on possible cognitive differences between personnel entering mechanical maintenance specialties, which include flight controls, and those in avionics maintenance specialties. Finally, an advantage of flight controls is their relative constancy over time (e.g., in contrast to avionics, which are frequently upgraded), providing lasting benefits from the instructional program generated by this study.

### Results

Bases for Skill Generalization. Task analyses to date have revealed a number of flight controls troubleshooting elements that are shared across aircraft systems, subsystems, and models. Our training focuses on these common elements to promote desired skill generalization.

Because most flight control systems consist of mechanical, hydraulic, and electrical components, what is learned about isolating faults in any of those types of components also applies to a number of other aircraft systems that utilize some or all of those same functional building blocks. For example, one of the best candidates for generalization is the landing gear, which also has

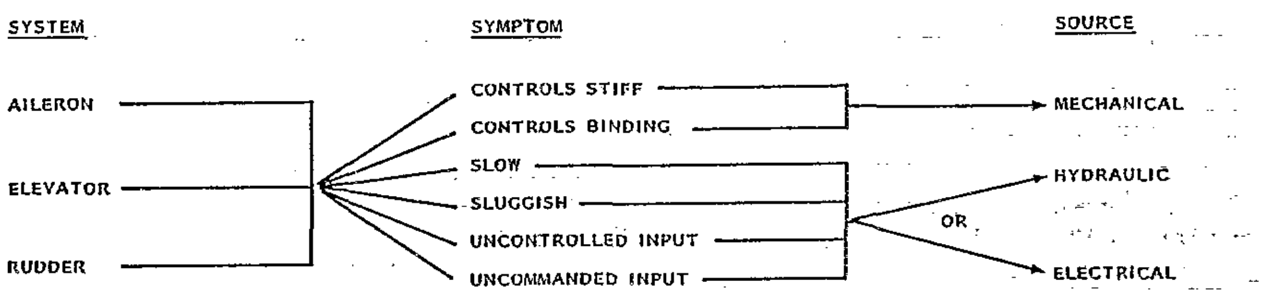


Figure 3. Some symptom-source associations for troubleshooting primary flight controls

mechanical, hydraulic, and electrical components and for which many of the same types of tests are needed to diagnose a failure. Considerable generalization is also expected within the flight controls of a particular aircraft, from skills directly taught for a particular subsystem (e.g., aileron) to those needed, but not taught, for a related subsystem (e.g., rudder) that has similar components and operating principles.

Expert Knowledge Composition. Our cognitive task analyses have indicated that troubleshooting experts are distinguished by their organization of diagnostic knowledge into series of symptom-source associations or rules. We have been identifying these associations, and they are being included in the curriculum to accelerate development of troubleshooting expertise.

As exemplified in Figure 3, well-learned symptom-source associations enable expert diagnosticians to quickly home in on the place in the system which is responsible for a given malfunction. Figure 3 also illustrates that these associations can sometimes be generalized across subsystems (aileron, elevator, and rudder in the case of primary flight controls) which are similarly constructed or serve related functions. Troubleshooting experts employ entire sequences of such rules to fully isolate faults (e.g., additional rules/associations would be used to distinguish between hydraulic and electrical faults for the example shown in Figure 3).

We are identifying these expert rules for incorporation into our tutorial instruction, teaching students what types of tests or replacements are advisable, given a particular symptom condition. Opportunities to practice and generalize these rules are provided in the accompanying troubleshooting simulations. This helps students to overlearn the rules sufficiently to automatically trigger appropriate diagnostic actions when a given symptom, or pattern of symptoms, is observed.

Another characteristic of expert troubleshooting, particularly in the context of complex systems such as flight controls, is attention to key interfaces. Knowing how these interfaces connect or control different components allows experts to make fewer, but more informative, tests than would most novices. Our intelligent tutorial instruction is designed to introduce students to the role of interfaces in troubleshooting strategies, and simulation exercises provide opportunities to apply these strategies.

Simulation as Knowledge Validation. In developing aircraft training simulations, we encountered a benefit not considered when beginning this study. Besides helping students to discover and apply new knowledge, the process of creating and testing equipment simulations serves as a rigorous means of debugging and validating the developers' knowledge of the system being taught.

An incomplete or incorrect understanding of the system, including its malfunctions, becomes quite obvious as the computer generates effects inconsistent with expectations for system performance. This, in turn, forces the instructional developers to reconsider the rules they have specified for equipment operation, which are also what they intend the students to learn.

Without such built-in, prior checks on instructor knowledge, students are too often subject to misconceptions or insufficiently specified information that undermine their future troubleshooting performances. However, by providing these safeguards for instructional content, our simulation development can even provide quality assurance for information delivered to students by means other than the computer simulations themselves, such as the content of lectures and training manuals.

Theoretical Framework. Finally, our cognitive analyses have suggested that troubleshooting is a particular form of problem solving that has been identified in psychology laboratory settings as rule induction, or inductive reasoning. Like rule induction, at least some aspects of good troubleshooting involve the recognition of a pattern in a series of objects or events (e.g., pressure readings, mechanical movements, etc.) This pattern, or rule, in turn, can be used to predict future system events (e.g., outcomes of tests, operational characteristics, etc.) and to identify deviations from the general pattern (i.e., malfunctions).

If further investigation bears out this relationship between troubleshooting and rule induction, it will provide a good theoretical framework to guide development of troubleshooting training. Previous research has already demonstrated substantial gains in rule induction performance through training,(3) and common cognitive processing demands across problem formats and content domains have been empirically determined.(4,5) This work has also suggested some sources of individual differences in solving such problems that are being considered as we individualize the ICAI program to the diverse entering abilities of student technicians.

## SUMMARY AND CONCLUSIONS

Cost-effective improvements in aircraft troubleshooting are attainable through a new type of apprenticeship program comprised of intelligent tutorial instruction and simulation exercises coached by an expert system. The ultimate effectiveness of this ICAI application, however, depends on prior analyses of both the troubleshooting tasks to be performed and the gaps between novice and expert capabilities which the training must bridge.

Our task analyses have revealed commonalities across aircraft equipment that form the focus of instruction for troubleshooting skill generalization. Likewise, distinguishing characteristics of experts have been identified. Such individuals organize their knowledge into symptom-source associations that enable them to quickly begin productive solutions when encountering a maintenance problem. They are also characterized by excellent knowledge of which test points in a system (e.g., key interfaces) yield rich information about sources of malfunctions. These types of knowledge are being incorporated into our ICAI to develop the problem solving efficiency demanded by the time pressures of combat.

Realistic simulations are being used to stimulate exploration and practice of solution rules/techniques introduced during tutorial instruction until they become automatically triggered during maintenance problem solving. These simulations also provide opportunities for students to induce their own fault isolation rules, generalizing from information provided during intelligent tutorials and from solutions demonstrated by the expert system during related simulations.

Further experimentation will be required to maximize troubleshooting generalization while keeping training time to a minimum. Interrelationships among diagnostic problems revealed during task analyses will be used to predict paths of troubleshooting generalization, from faults for which solutions were explicitly taught to new, but related, faults on different equipment/subsystems. Actual student performances along these paths will then be monitored to determine adjustments needed in the number and variety of simulation exercises, as well as in the content of tutorial instruction, to obtain a given level of mastery and skill generalization. The instructional media (e.g., computer text, graphics, digitized photographs, etc.) will also be systematically manipulated to find the combination that best moves students to expert levels of performance.

It is expected that individual differences in cognitive skills will interact with the instructional variables being studied, making the learner-adaptive capabilities of ICAI especially valuable for improving maintenance problem solving. Fortunately, we have discovered relationships between troubleshooting processes and a cognitive theory of rule induction. They will provide a productive framework for guiding further exploration of the effects of individual differences and instructional variables on troubleshooting skill development.

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