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AN INTELLIGENT TUTORING SYSTEM FOR SPACE SHUTTLE DIAGNOSIS

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ABSTRACT

Intelligent Tutoring Systems (ITSs) transcend conventional computer-based instruction. An ITS is capable of monitoring and understanding student performance thereby providing feedback, explanation, and remediation. This is accomplished by including models of the student, the instructor, and the expert technician or operator in the domain of interest. The space shuttle fuel cell is the technical domain for the project described below.

One system, Microcomputer Intelligence for Technical Training (MITT), demonstrates that ITSs can be developed and delivered, with a reasonable amount of effort and in a short period of time, on a microcomputer. The MITT system capitalizes on the diagnostic training approach called Framework for Aiding the Understanding of Logical Troubleshooting (FAULT) (Johnson, 1987). The system's embedded procedural expert was developed with NASA's CLIPS expert system shell (Culbert, 1987).

MITT was conceived and sponsored by the Air Force Human Resources Laboratory, Brooks Air Force Base, Texas. The research, development, and evaluation of MITT was completed with cooperation from NASA at the L.B. Johnson Space Center, Houston, Texas.

INTRODUCTION

Intelligent Tutoring Systems (ITSs) are instructional systems that deliver training in a manner comparable to that of a human tutor. ITSs deliver instruction, interact with students, and structure subsequent instruction based on student performance. To provide such instruction, ITSs must contain an understanding of a specific domain, a means to model student understanding of that domain, and a component containing pedagogical guidelines for providing feedback and remediation. These components must surround an instructional environment. The instructional environment must have a reasonable interface to the student user. The components of a generic ITS are shown in Figure 1 (Johnson, in press). There are many recent publications that offer thorough definitions of ITSs and describe existing systems (Psotka, Massey, & Mutter, 1988; Polson & Richardson, 1988; and Wenger, 1987).

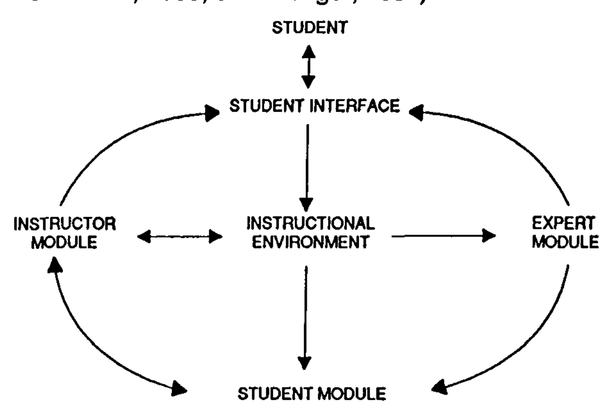


Figure 1. Components of an Intelligent Tutoring System

This paper describes a six-month research effort in which mature computer-based instruction (CBI) for diagnostic training was integrated with the NASA expert system shell, C Language Integrated Production System (CLIPS), to create a fully operational ITS on a microcomputer. The system is called Microcomputer Intelligence for Technical Training (MITT).

Although ITSs have been around for nearly twenty years, they have not emerged as common components in training departments. Instead, they have remained as research topics in industry, government, and university laboratories (Johnson, in press). The purpose of the MITT project was to prove that ITSs can be developed in a reasonable amount of time for a reasonable price. Also, the MITT developers wanted to show that ITS technology is sufficiently mature to contribute to an operational training environment.

COMPUTER-BASED INSTRUCTION

To develop an instructional environment for MITT, Search Technology, Inc. capitalized on its more than 10 years of research experience with computer-based simulation for diagnostic training. That research (Hunt & Rouse, 1981; Johnson, 1981, 1987; Johnson & Rouse, 1981; Rouse and Hunt, 1984) was characterized by an evolving set of computer simulations and extensive experimental and real-world evaluations. This R&D was conducted in diverse domains, such as automotive mechanics, aviation mechanics, communication/electronics, and nuclear safety systems. Search Technology's CBI research began as an attempt to understand how humans gather and process information in problem-solving situations. This led to research into the effects of training on problem-solving behavior. From this research, a variety of training concepts were developed and evaluated in laboratory and field tests. The diagnostic training simulations that emerged from this research were Troubleshooting by Application of Structural Knowledge (TASK) and Framework for Aiding the Understanding of Logical Troubleshooting (FAULT). Both simulations are described by Rouse and Hunt (1984).

FAULT, proven in a variety of instructional domains, is at the heart of the MITT system. It uses a hard copy functional flow diagram along with an on-line display for student options, test results, and feedback. FAULT is a simulation that permits the user to engage in the same information processing that would take place during real equipment troubleshooting. This includes actions such as checking instruments, obtaining symptomatic reports from an operator, forming hypothesis, selecting tests, and identifying parts for replacement. FAULT simulations developed prior to MITT included a limited degree of intelligence that provided student advice and feedback (Johnson, Norton, Duncan, & Hunt, 1988).

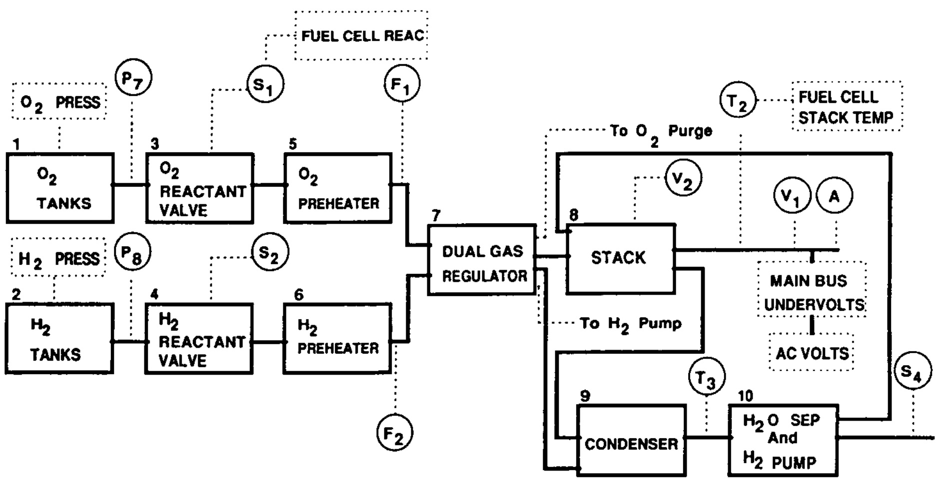
THE MITT SYSTEM

The MITT system consists of five parts shown in Figure 1: the instructional environment, the student interface, the expert module, the student module, and the instructor module. This section describes each of the modules and how they communicate to form the Intelligent Tutoring System.

The Instructional Environment

MITT's instructional environment is the FAULT simulation. Perhaps the greatest strength of the FAULT simulation is the simplicity of the system's representation. Figure 2 shows MITT's functional flow representation of the space shuttle fuel cell. Each part

FUEL CELL CRYO SYSTEM



GAUGE	NAME	LOCATION(S)	EFFECT
S1	O2 Reac Vlv Tb	R1C, Syssumm1, & Spec 69	MCC3
S2	H2 Reac Vlv Tb	R1C & Spec 69	MCC4
S4	Ph of H2O	Spec 69	T10-8
F1	O2 Flow Rate	Spec 69	T5-7
F2	H2 Flow Rate	Spec 69	T6-7
V1	Volts	Syssumm1, Spec 67 & Spec 69	T8-9
V2	Volts Monitor/SS2	Syssumm1 & Spec 69	MCC8
T2	Stack Temp	Syssumm1, Spec 69, & O2	T8-9
T3	Exit Temp	Syssumm1 & Spec 69	T9-10
P7	O2 Tank Pressure	Syssumm2, Spec 68 & O2	T1-3
P8	H2 Tank Pressure	Syssumm2, Spec 68 & O2	T2-4
A	Amps	Syssumm1, Spec 67, Spec 69 & F9	T8-9

Figure 2. MITT Fuel Cell Functional Flow Diagram

in the system is represented as a node in a network. MITT's simple, single functional relationship helps the student create a mental model of the technical system.

The Student Interface

Although each module of an ITS is critically important, it is the user interface that ultimately delivers the instruction to the user. The interface must allow easy interaction with the simulation. Also, the outputs of the expert, student, and instructor modules must be completely integrated with the student interface in order to be effective and unobtrusive.

A mouse is the primary user input device, although a keyboard may also be used at any time. The cursor, controlled by either the mouse or the keyboard, can be moved within each menu to select student diagnostic options. On certain screens, extensive data are available as shown in Figure 3. For the simulation to know precisely what data the student is requesting, it is necessary for the user to click on the *XXX* area (see column 3 in Figure 3) to obtain the information.

2011/ /069 FUEL CELL 4 /02/11:48:21
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		1	2	3
VOLTS		30.5	29.7	XXX
AMPS		208	208	XXX
FLOW	02	4.4	4.5	XXX
	H2	0.5	0.6	XXX
REAC	02	OP	OP	XXX
	H2	OP	OP	XXX
STACK	T	+203	+204	XXX
EXIT	T	150	150	XXX
COOL	T	72	70	XXX
	P	60	60	XXX
PUMP				
H2 PUMP		0.4	0.4	XXX
READY		RDY	RDY	XXX
H20 LN	T	134	133	134
VLV	T	72	70	70
EC	A			
HEATER	B			

H20 RLF LINE	T	90
NOZT	A	210
	B	210
HTR SW		
PURGE LN 02	T	51
H2	T1	62
	T2	39
H20 LINE PH		XXX

FC

	1	2	3
PH			XXX
V SS1	17	11	14
SS2	10	13	XXX
SS3	19	17	13

F1 HELP F7 BACK UP ONE F9 BACK TO START

Figure 3. CRT Display Requiring Specific Information Request Areas

The Expert Module

MITT's expert module represents the system in two ways. It has both a procedural and a functional expert. The procedural expert (PE) maps symptoms to suspect systems and components with collections of if-then rules. These symptoms include information such as annunciator lights and instrument indications. The functional expert (FE) uses one or more connectivity matrices to represent various functional relationships among the parts of the system.

The procedural expert

The procedural expert is a series of rule-based statements. It contains information in the form of advice regarding specific NASA troubleshooting procedures for the space shuttle's fuel cell. At any stage during diagnosis of a malfunction, the student can request procedural advice. The PE gives advice according to the order in which gauges, controls, or panels have been seen by the student. Advice is given only when it is requested from the MITT menu by the student. This procedural advice suggests the next step to take in the diagnosis of a malfunction. The student may follow the advice that is given or choose from other menu options.

PE development required an analysis of existing NASA troubleshooting procedures. These procedures were broken down into steps or actions that are likely to be used by the student. Each action corresponds to the reading of simulated gauges, controls, or panels available in the shuttle. Search Technology's analysis of the MITT project had to ensure that the student had some means to accomplish a given NASA procedure within the constraints of the simulation.

Each statement of advice is linked to a logical test. For example, if the orbiter's primary annunciator panel (F7) has been seen and the front gauge panel (F9) or cathode-ray tube (CRT) display System Summary 1 has been seen, then an advice statement describes what has been seen, what conclusions can can be drawn, and what actions are appropriate. All of the advice statements for the six malfunctions are incorporated into approximately 60 rules. Additional procedural intelligence can be incorporated by merely adding to the established rule base.

The functional expert

The functional expert (FE) is based on the functional connectivity among the system components. For example, if part B depends on part A and part A has failed, then part B will be adversely affected. Also, part B will adversely affect parts which depend on it. This functional understanding permits the expert to calculate how failures propagate through the system by following the functional topography.

The student has the option to interact with this expert by requesting FE advice while working on a problem. The FE provides assistance based on the functional structure of the system and the student's previous actions. The FE also communicates with the student module to monitor changes in the feasible set of failures based on each student action.

Expert integration

The experts must have the means to communicate with each other. During MITT's development, this was accomplished by creating an equivalency table between gauge readings and topographic tests. For example, a reading of the O2/H2 flow on a gauge may be the same as a test between two parts of the functional flow diagram. As far as MITT was concerned, they are the same. All of the tests were translated to gauge readings to match the format of the PE. In addition, the gauge readings were translated to functional flow tests for the FE.

The Student Module

The student module creates a model of the student by tallying the student's actions throughout the simulation. The student model is updated by the FAULT simulation and the expert module. The data from the student model is used by the instructor module to determine when advice is appropriate.

MITT has a student model that is current for each problem. The model includes tests the student has taken and results of these tests. The model keeps track of the number of times the student uses an option from the primary simulation display as well as the number of accesses to each orbiter gauge, annunciator, or CRT. The model also keeps track of the type of errors noted by the functional expert. The student module provides feedback upon completion of each problem as shown in Figure 4.

Congratulations! You have corrected the problem.

Number of students completing this problem:	78
Number of students who quit before solving:	2
Number of students who received a time out:	6

	Your	Average
Number of minutes for diagnosis:	7	8.4
Number of errors made:	2	1.6
Number of displays accessed:	14	17.3
Number of times procedural advice used	1	1.8
Number of times functional advice used	2	1.3

Figure 4. MITT Feedback at Problem Completion

The Instructor Module

The instructor module is a rule-based routine that pinpoints certain student errors and intervenes as they occur. The types of errors detected include student actions that result from a student misunderstanding of either the MITT system or of simple troubleshooting procedures. The advantage to this approach is that the instructor module provides generic advice that promises to be effective for current and future simulations.

The instructor module was designed to help guide the student to the most appropriate segment of the MITT system. Instead of redundantly explaining something, it suggests where the student should look for more information. In this sense, the instrucor module actually works more like a reference librarian than a teacher. The advantage to this approach is that only those who need reference material use it.

The entire MITT system is designed to deliver instruction in such a way that even novices can easily use the system. The system includes help for using the MITT simulation and contains technical information and diagnostic advice on the fuel cell's domain. MITT is student driven with complete learner control. Only under exceptional circumstances does the instructor module intervene and redirect the student from exploring his own paths.

Hardware

The hardware system used for the development and delivery of the MITT ITS was an IBM-AT (or an IBM-compatible system). The system requires 640 Kb of random access memory (RAM) and a hard disk. Presently, an Color Graphics Adapter (CGA) card and color monitor are needed. A mouse is recommended, but optional.

The rationale for using IBM-ATs is straightforward. First, the equipment is affordable and more likely to be found in research laboratories and (more importantly) training installations. When a group decides to use MITT, they will not have to purchase expensive, dedicated AI workstations. Second, IBM-ATs have all the necessary speed, storage, hardware and software support, and other capabilities to deliver the required level of intelligent tutoring. In addition, IBM-ATs offer readily available off-the-shelf peripherals for interface to video disk and other computers.

CLIPS

MITT is written in C. By capitalizing on CLIPS, MITT processes rules for the various modules without using LISP. Therefore during MITT's development, CLIPS was a convenient tool to use for several reasons. It can be embedded into existing C code, it has an built-in inference engine, the rules are simple to create, and CLIPS itself is easy to learn. In addition, CLIPS is highly portable across computer systems. CLIPS runs on IBM-ATs and IBM compatibles, and it is inexpensive (i.e., free for government use).

The disadvantage to using CLIPS, during MITT's development, was that Search Technology did not have a reliable, compiled version of CLIPS at the time MITT was completed. The uncompiled CLIPS version caused a delay in the system's response time to the student. The new, compiled version of CLIPS will increase the speed with which procedural advice is given, thereby improving user acceptance of MITT.

MITT EVALUATION

Evaluation can be divided into two stages: formative and summative evaluations. Formative evaluation takes place during software design and development. Summative evaluation refers to the software's value following development. For this short effort, the formative evaluation was most important.

Formative Evaluation

The primary goal of formative evaluation is to keep potential users informed as to ongoing development and the expected final product. Formative evaluation permits developers, subject matter experts, and prospective users to be constantly informed and able to make real-time changes in design. It also prevents the notion that "it is too late to change that now."

The majority of MITT's formative evaluation was accomplished by the ongoing interaction between the developers and personnel from NASA and AFHRL. During the program's development, Search Technology followed a proven evaluation plan for CBI development (Maddox & Johnson, 1986). The plan ensured that software evaluation was performed using a three-step process: measuring compatibility, understandability and effectiveness. Compatibility refers to the extent to which the user is able to see the computer displays and reach the pointing devices. Displays must be legible, and all colors must be easily discernible. Understandability is concerned with ITS output and required user input. Users must be able to understand what the system is telling them and what they must tell the system. In addition, the system input requirements must aligned with the student's prior knowledge and training. Effectiveness is similar to summative evaluation which is explained below.

Summative Evaluation

Summative evaluation takes place once the software is complete. It is a summary concerned with the effect of the training on student performance. MITT is not ready for a classic summative evaluation because only the first 6-month phase of the work is finished. However, the first phase did undergo two pseudo-summative evaluations that served as a way to define the steps needed for the next phase of MITT's development, tentatively called MITT II.

The first stage of the summative evaluation was conducted by Search Technology and NASA. This evaluation took place over a 2-day period at the Johnson Space Center. During that time, 17 NASA employees used MITT. These people included astronauts, flight controllers, CBI developers, AI researchers, technical instructors, and a training manager. The goal of the evaluation was to obtain a preliminary assessment of user acceptance and to insure that the ITS was complete and technically correct. User acceptance was overwhelmingly positive.

The second stage of the summative evaluation was conducted by AFHRL and NASA, again at Johnson Space Center. For this evaluation, MITT was used by 15 flight controllers for approximately 3 hours each. Again, the MITT ITS simulation was well received by the students. Many users commented that they saw value in the problem-solving approach to training presented by MITT. The users were impressed with the fact that they could proceed at their own pace with their own problem-solving style. The students were also satisfied with the advice they received from the functional, procedural, and instruction experts.

The second evaluation pointed out areas of the MITT system that could be improved in subsequent versions of MITT. For example, it would be worthwhile to modify the on-line shuttle schematics to more closely resemble the functional flow diagrams. Some users commented that they would prefer higher fidelity displays of shuttle instrumentation. In addition, the current MITT problem knowledge base must be embellished to include a greater variety and number of problems.

Comments from NASA's instructional staff and training managers have been very positive. NASA is anxious to proceed with MITT II's development. Their first concern is to enhance the fuel cell knowledge base so that it can provide daily operational training to supplement existing classroom and simulator training. They also want the capability to build knowledge bases for additional space shuttle and space station subsystems. A goal of the MITT II program is to develop software tools and knowledge engineering techniques that will place an increasing amount of ITS development in the hands of training department personnel. These tools will help to decrease the costs of ITS development and further increase ITS availability.

CONCLUSION

MITT has clearly demonstrated that Intelligent Tutoring Systems can be developed in a reasonably short period of time at a reasonable cost. MITT has also shown that ITSs can be developed and delivered using off-the-shelf microcomputers. Most importantly, the MITT project has demonstrated that ITSs do not have to remain "laboratory rats", but instead can be viable components of operational training departments.

ACKNOWLEDGMENTS

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