E-3A MAINTENANCE PROCEDURE SIMULATORS - A NEW BREED OF CATs

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ABSTRACT

Computer-Aided Trainers (CATs) for mission avionics subsystems on the E-3A "Sentry" aircraft simulate BITE outputs to support self-paced practice in flight line maintenance procedures. They represent a new breed of CATs evolved through application of the Instructional System Development (ISD) process and a unique synthesis of hardware, software and "courseware" to satisfy organizational maintenance training requirements. This paper is in two parts. Part I summarizes the application of the ISD process used to identify requirements for training and training equipment. Part II concentrates on the evolution of the maintenance trainers, emphasizing the system development using as a case study the E-3A Maintenance Procedure Simulator (MPS) for the AN/ASN-118 Navigation Computer System.

PART I: SUMMARY OF ISD APPLICATION

Selection of CATs as the most cost effective method for satisfying E-3A training was strongly influenced by results of a 1974-76 effort to define training equipment requirements for four major groups of E-3A mission avionics equipment prior to delivery of the first aircraft in March 1977. Table 1 lists these four equipment groups and the specialty codes and titles for the four types of technicians who must be trained to maintain them.

Scope of ISD Effort

When properly applied, a joint contractor/government ISD effort can provide a system acquisition program director with essential information needed to define a cost-effective "mix" of classroom, laboratory and on-job training. The E-3A Sentry Engineering Division (YWE) may be unique, in that since the inception of the Airborne Warning and Control System (AWACS) program, a separate section has been responsible for all human factors, training, and training equipment, with contract technical support from the American Institutes for Research (AIR), a nonprofit firm specializing in applied education and training research. In the E-3A program, collaboration between contractors and government personnel in the ISD process was achieved by a series of working-level Technical Interchange (TI) meetings during the 18-month period from September 1974 through January 1976. A study contract to develop specifications for training equipment was initiated by Boeing, the E-3A prime contractor, in December 1974.

Inputs available to the government/contractor ISD team included:

- Draft Training Plan
- Qualitative/Quantitative Personnel Requirements Information (QQ PRI)
- Aerospace Ground Equipment (AGE) Plan
- Optimum Repair Level Analysis (ORLA) Reports
- Reliability/Maintainability Allocations, Analysis and Assessment Reports

TABLE 1. AWACS MISSION AVIONICS EQUIPMENT

AWACS MISSION AVIONICS EQUIPMENT	AFSC	AIR FORCE SPECIALTY TITLE
Data Processing	305X4	Electronic Computer Systems Repairman
Communications	328X0	Avionic Communications Specialist
Surveillance Radar	328X2	Airborne Early Warning Radar Specialist
Navigation/Guidance	328X4	Avionic Inertial and Radar Navigation Systems Specialist

Figure 1 shows a functional flow diagram of the training equipment requirements analysis based on the procedures defined in AFP 50-58 "Handbook for Designers of Instructional Systems." Representatives of Air Training Command (ATC), Tactical Air Command (TAC), E-3A SPO personnel and AIR participated in TI meetings with Boeing training specialists during the ISD effort, which was divided into six phases:

(1) Review AWACS equipment and AGE to establish maintenance task descriptions.

(2) Determine job performance and knowledge requirements for each Air Force Specialty Code.

(3) Establish maintenance training objectives for each Air Force Specialty Code.

(4) Determine training media requirements to accomplish training objectives.

(5) Define candidate training equipment configurations needed to satisfy media requirements.

(6) Develop detailed specifications for preferred training equipment configuration selected for each Air Force Specialty Code.

The outputs of the ISD study effort included a comprehensive technical data package containing the "Training Equipment Preliminary Requirements Report" and a set of draft specifications and a set of budgetary cost estimates. The methods used to define the training equipment are described below, using the AN/ASN-118 as an example.

Maintenance Task Analysis

Using the procedures defined in Volume II of AFP 50-58 as a guide, maintenance tasks were analyzed independently by ATC representatives and the prime contractor. The team analyzed the organizational maintenance tasks defined explicitly or implicitly in the QQPRI and AGE Plan. The Boeing team analyzed intermediate (shop) maintenance tasks resulting from the ongoing ORLA and R/M analyses. Results were consolidated on standard ATC task description worksheets to produce a common baseline for definition of learning objectives.

Definition Of Learning Objectives

Formal learning objectives for each class of related tasks (e.g. flight-line checkout procedures) were first defined independently by ATC and Boeing, then consolidated on a set of Learning Objective Worksheets (LOWs) developed by AIR for this purpose. Each LOW identified the learning objective, the standard for its measurement and the analyst's judgement regarding the best learning media to support the achievement of the objective. Differences in media recommendations were resolved at TI meetings. As a timely byproduct, the scope and content of ATC Course Training Standards for resident training courses, field training at TAC bases, and Type I cadre training at contractor and subcontractor facilities were also established at these TI meetings.

Evaluation Of Training Configurations

For each E-3A mission avionics system, two or more "candidate" training equipment configurations were identified and rated on 26 different characteristics grouped in four categories as illustrated in Figure 2. Candidates generally represented the extremes of full simulation and actual operational equipment, with some mixed cases combining computer-assisted instruction (CAI) with mockups and actual operational end-items. Thus, for the AN/ASN-118 system, Candidate A was defined as an Actual Equipment Trainer with three student stations; Candidate B was a Computer-Aided Training System using two student CRT terminals to guide students in the operation of front panel mockups; Candidate C was a mixed system combining features of the first two configurations.

Tasks assigned to Categories 1 and 2 were classified into the seven types used by the USAF Human Resources Laboratory for development research on Job Performance Tests for electronic technicians. For the third category of Training Suitability, each candidate was evaluated against qualitative criteria determined by a training literature review to yield high training effectiveness. The extent to which each candidate would minimize support requirements was rated in terms of the impact on facilities, computer programming support, unique test equipment, and overall ease of maintenance.

For each of the 26 traits shown at the left in Figure 2, analysts entered a rating taken from the following five-point scale:

Rating Description	Rating
Little or no capability	1
Partially satisfies criteria	2
Satisfies most criteria acceptably	3
Satisfies all criteria acceptably	4
Satisfies all criteria exceptionally	5

The weighting factors shown in Figure 2 were based on a three-point scales (low/moderate/high) for rating the task proficiency training suitability, and the impact on support requirements. The products of each weight and candidate rating were entered in the "adjusted" column, then divided by the number of criterion items to obtain a "normalized" rating between 1 and 5 for each major category. Regrettably, the procedure used did not include multiple raters or inter-rater reliability measures. As indicated in Figure 2, the Computer-Aided Training system (Candidate B) was rated highest, and was therefore recommended to support training of 328X4 personnel in maintenance of the AN/ASN-118 system.

The E-3A prime contractor's draft report detailing the ratings and rationales for each of the four recommended training equipment configurations was reviewed at a TI meeting in September 1975. Results were curious and disappointing

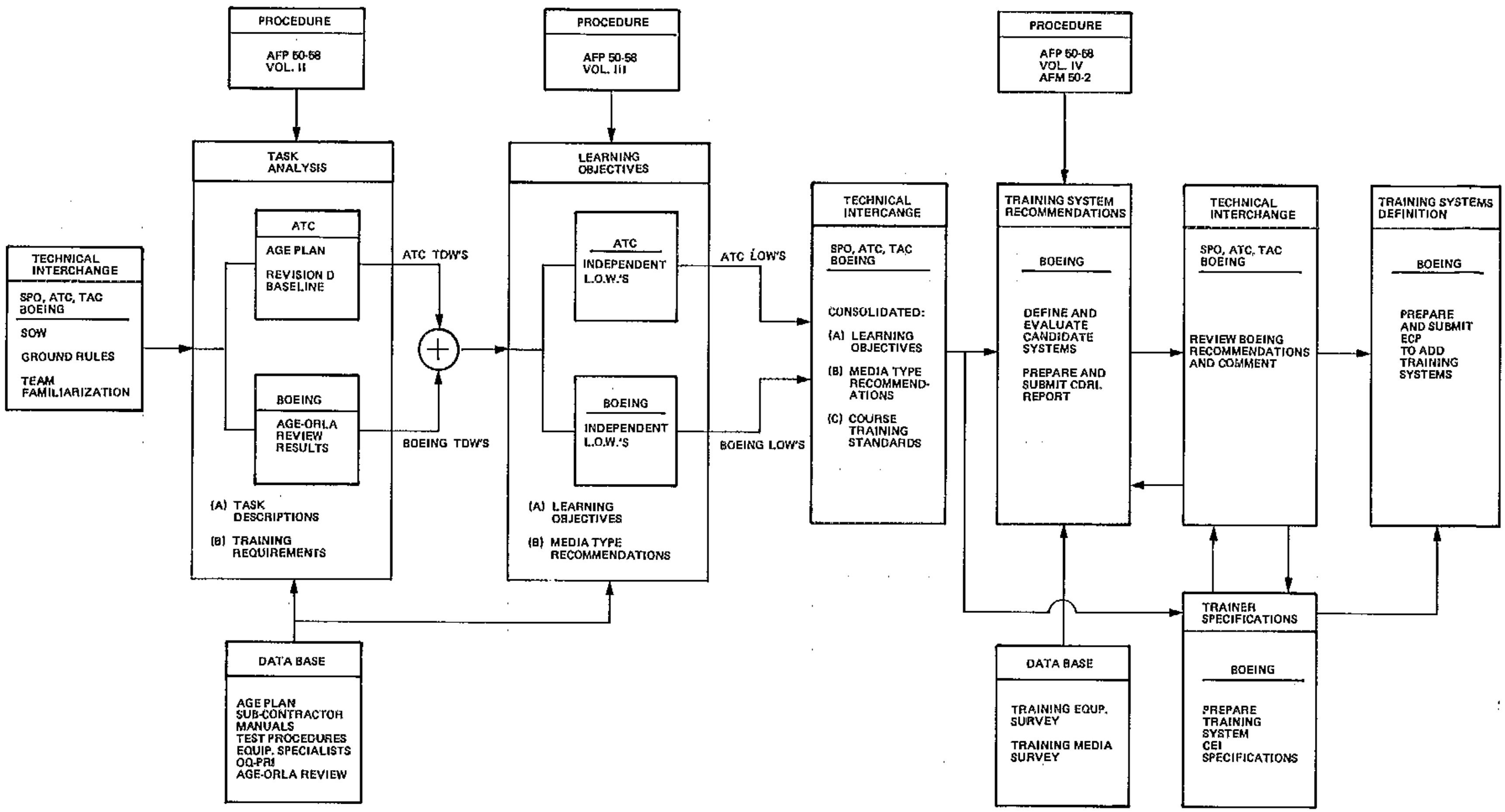


FIGURE 1. FUNCTIONAL FLOW DIAGRAM
AWACS MAINTENANCE TRAINING EQUIPMENT REQUIREMENTS ANALYSIS

CANDIDATE SYSTEMS DESCRIPTION

- A — ACTUAL EQUIPMENT TRAINING SYSTEM (AET)
- B — COMPUTER AIDED TRAINING SYSTEM (CATS)
- C — COMBINED AET/CATS

ITEM NO.	TRAINING EQUIPMENT EVALUATION CRITERIA TITLE	WEIGHING FACTOR	TIMES	CANDIDATE SYSTEM RATING A	B	C	D	E	EQUALS	ADJUSTED RATING A	B	C	D	E	DIVIDED BY NO. OF APPLICABLE CRITERIA ITEMS EQUALS	NORMALIZED RATING A	B	C	D	E
1.	ONBOARD TASK TRAINING																			
1.1	*ACCESS*	1		4	4	4				4	4	4								
1.2	VISUAL INSPECTIONS	1		4	3	3				4	3	3								
1.3	PERFORMANCE CHECK	2	X	5	5	5			=	10	10	10								
1.4	FAULT ISOLATION	2		4	4	3				8	8	6								
1.5	ALIGN AND ADJUST	2		4	4	4				8	8	8								
1.6	REMOVE AND REPLACE	1		5	4	4				5	4	4								
1.7	TEST EQUIPMENT USE	3		4	5	3				12	15	9								
									SUM	51	52	44			÷ 7 =	7.3	7.4	6.3		
2.	SHOP TASK TRAINING																			
2.1	VISUAL INSPECTIONS	2		5	4	5				10	8	10								
2.2	PERFORMANCE CHECK	3		5	5	5				15	15	15								
2.3	FAULT ISOLATION	3	X	5	4	5			=	15	12	15								
2.4	ALIGN AND ADJUST	NA		—	—	—				—	—	—								
2.5	REMOVE AND REPLACE	2		5	4	5				10	8	10								
2.6	TEST EQUIPMENT USE	3		4	5	4				12	15	12								
									SUM	62	58	62			÷ 5 =	12.4	11.6	12.4		
3.	TRAINING SUITABILITY																			
3.1	FEEDBACK	3		2	5	3				6	15	9								
3.2	PARTICIPATION	3		4	5	4				12	15	12								
3.3	REALISM	2	X	5	3	4				10	6	8								
3.4	SELF-PACING	2		3	5	4			=	6	10	8								
3.5	SAFETY	3		3	5	4				4	15	12								
3.6	RESPONSE RECORDING	1		1	5	3				1	5	3								
3.7	AVAILABILITY	3		2	5	3				6	15	9								
3.8	FLEXIBILITY	2		3	4	3				6	8	6								
									SUM	51	89	67			÷ 8 =	7.0	11.1	8.4		
4.	SUPPORT REQUIREMENTS																			
4.1	SUPPORT EQUIPMENT	2		4	4	4				8	8	8								
4.2	FACILITY	2		3	5	4			=	6	10	8								
4.3	MAINTENANCE	2	X	1	4	2				2	8	4								
4.4	COMPUTER PROGRAMS	2		4	1	2				8	2	4								
4.5	NEW HARDWARE	2		5	3	4				10	6	8								
									SUM	34	34	32			÷ 5 =	6.8	6.8	6.4		

FIGURE 2. AWACS TRAINING SYSTEM EVALUATION WORKSHEET FOR NAVIGATIONAL COMPUTER SYSTEM

to all concerned. Responding to historical ATC and TAC preferences for actual equipment for maintenance training, the contractor offered to supply actual equipment trainers at an estimated cost of approximately $35 million. This sum did not include costs of support equipment required to meet reliability/maintainability specifications. By January 1976, when costs for support equipment were included, the proposed costs for actual equipment trainers had ballooned to approximately $50 million. This sum greatly exceeded the funds programmed for maintenance training equipment for AWACS mission avionics.

E-3A SPO Cost/Benefit Analysis

Faced with this situation, human factors and training specialists in the SPO prepared, with AIR assistance, a Cost/Benefit Analysis showing the amortized cost per trainee for the relatively small numbers of trained personnel (11 to 70 per year) required to man TAC maintenance positions for the fleet of 15 aircraft then under contract. Prorated over a 15-year life cycle, maintenance training equipment costs would have ranged from $21,000 to $80,000 per trainee. This study postulated and explored the consequences of a decision to drastically limit MTE procurement to static devices and visual aids for classroom training (relying on the T.O.s and student handouts), deferring actual "hands-on" practice to on-the-job training at TAC bases. This "devil's advocate" approach produced prompt and constructive responses from TAC and ATC, generally favoring a pragmatic mix of a) selected end-item equipment with which ATC would construct its own communication trainer; b) second-shift operations at TAC bases to train computer maintenance technicians using already-available AWACS operator training equipment; and c) low-cost front-panel simulators for the radar and navigation training equipment.

In March 1976 the E-3A SPO approved this pragmatic approach to a cost effective solution of training requirements. This approval was qualified by a recognition that availability of adequately defined procedures in technical orders should be a prerequisite to purchase of testing equipment. In May 1976, ATC proposed design guidelines and preliminary functional requirements for a front-panel simulator to support training for the navigation systems. An ATC preference for the extensive use of off-the-shelf equipment in the simulators and a competitive procurement for them was endorsed by the E-3A SPO at a TI meeting in June 1976, at which time AIR commenced work on the Prime Item Development Specification (PIDS). Competitive bidding resulted in award of a contract to Honeywell on 30 May 1978 and the ASN-118 (T1) simulator for the E-3A Navigation Computer System was delivered to Keesler Technical Training Center 18 months later in December 1979.

PART II: THE MAINTENANCE PROCEDURE SIMULATOR (MPS)

Trainer design and development is a disciplined symphony made up of concepts, components and people. The maintenance trainer is a recent addition to the host of, among others, operator and operational trainers for sonar and avionic systems. Upon first look at the maintenance trainer, one can get lulled into a feeling that these type of trainers are relatively simple requiring less development rigor and discipline than previous device types. This would be a serious mistake in both time and money.

Maintenance trainers primarily use off-the-shelf components, well-proven equipments, all within today's technology. Difficulties in development schedules and cost arise because from past experience we typically estimate that the complexity of the device is equivalent to the complexity of the hardware. Hence, based on previous experience, we tend to underestimate the total scope of effort. Although the hardware is straightforward, the maintenance trainer is complex in the software and instructional features domain. The development approach for the maintenance trainer device must be carefully conceived, well-defined through specification and controlled through management disciplines.

The E-3A MPS Design Concept

The purpose of the E-3A MPS is to supplement classroom training of organizational level maintenance personnel on the AN/ASN-118 Navigation Computer System (NCS). The MPS is designed to demonstrate operation and checkout of the NCS. This includes the simulation of malfunctions and maintenance procedures. The MPS functions as a procedural trainer in that the following maintenance can be performed:

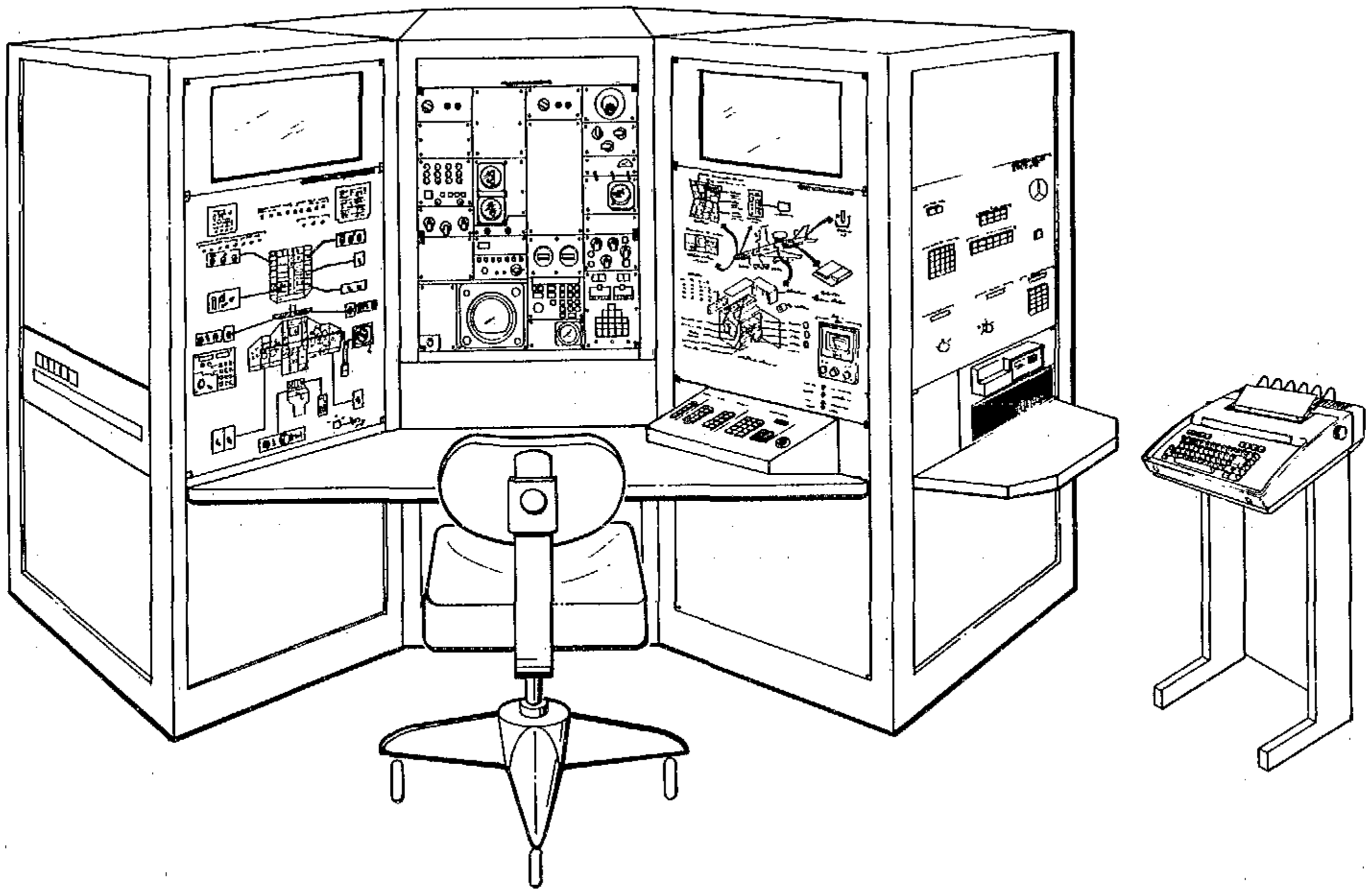
1. Fast System Checkout
2. Complete System Checkout
3. Trouble Analysis
4. Subsystem Performance Checks
5. Post Replacement Checkout Procedures

The MPS is augmented with real-time models in order to support part task training on the Inertial Navigation System (INS) as well as the NCS. A mix of simulated and real components for various E-3A avionic equipments are mounted on flat panels to provide hands-on manipulation of equipment during lessons. A pictorial of the device is presented in Figure 3

The Detail Design Specifications

A formal method to clarify a PIDS and document the system definition is necessary for development contracts. A first step towards achieving this objective is to make a comparison of the PIDS and the submitted proposal. The PIDS provides the information on what is required, the proposal provides information on what is priced. Any contradictions in the intent of these documents should be clearly identified as early as possible in the

Figure 3. E-3A Maintenance Procedure Simulator



project and result in specification changes. During the definition phase, all other clarifications should also be prepared and submitted as changes to the PIDS. Formal changes provide a clear trail as to what agreements have been reached between customer and contractor. The updated PIDS serves as a functional baseline for detailed product and software specifications.

A maintenance trainer, such as the E-3A MPS, is not meant to exactly duplicate all of the workings of the original equipment. The specifc functions and malfunctions of the operational equipment must be specified prior to software development and fabrication.

With a clearly defined PIDS, plus detailed maintenance procedures, a Computer Program Development Specification (Part I software requirement specification) can be drafted. The CPDS maps the software requirements from the PIDS into stand alone documents. Care must be taken in generation of the CPDS to present requirements, not implementation. It is important not to design the software system in the CPDS as this often precludes functional group participation and can lead to a less than robust software design.

To achieve system definition for the E-3A MPS, a System Specification was generated. This was an internal working document, which defined the system concepts and allocated functions to hardware, software and courseware. It was accessible to the project team and communicated the system as it evolved through the definition phase. This document was allowed to become obsolete upon conclusion of the design phase with the issuance of product and software specifications.

The Software System

In general, software systems for maintenance trainers interface with a wide variety of peripherals as well as panel(s) with multiple switches, rotaries, analogs, keyboards and other miscellaneous components which represent various aircraft subsystems. The software system provides the functional capability to allow for interface with the instructor for lesson preparation and control, as well as student monitoring. The functional capability to allow student interface with the trainer must also be provided.

The CPDS provides to what extent the student and instructor has to interface with the device. Also provided is the degree to which various components are required to be simulated.

The software architecture for the E-3A MPS is presented in Figure 4. It represents the approach Honeywell developed to meet the E-3A MPS requirements. The system is based on transposing Technical Orders (T.O.s) into an intermediate language, and compiling that language to form a data base. During a lesson the data base is used to provide the instructional portions of the simulation.

Specifically, the T.O.s are transposed using the Courseware Author's Language (CAL). The CAL was developed specifically for this purpose and Provides a productive means of presenting T.O. information in a high order language. The CAL is compressed through use of the Courseware Author's Language Generator (CALGEN). CALGEN takes the higher order language and transforms it into a compressed data base called Primitive Courseware Language (PCL). CALGEN provides error diagnostics and various user aids.

The application software is composed of two primary parts: specific trainer software and the Procedure Monitor. The specific trainer software is composed of the input/output processors, real-time model functions, and the instructor/trainee processors. The Procedure Monitor is the real-time interpreter which translates the PCL into actions based upon panel inputs.

Honeywell feels that this architecture is flexible and allows for change. This is important in maintenance trainers in that panel components can change as well as fidelity requirements over the life of the system.

For the E-3A MPS, two specific devices, the INS and NCS, were to be high fidelity, real-time simulations. Defining how the INS and NCS worked to the extent necessary was done very well. The INS and NCS work well enough to "fool" the student as well as the instructors into believing that they are actual devices. To give an example of the degree of fidelity, the INS activated switches on depression while the NCS activated switches on release, this was simulated in the trainer. In interfacing these models with courseware, two concepts should be kept in mind.

1. Courseware/software interfaces should be as simple as possible.

2. Courseware interfaces should be as transparent to the software as possible.

These aforementioned items will aid in making the software and courseware development simpler.

The Courseware

The courseware starts out as a T.O., and winds up as a compressed data base stored on disk. The manner in which the courseware evolves from T.O. to language is called T.O. Annotation. The annotation of T.O.s is a result of training analysis and human factors engineering. As a result of the annotation, the T.O. becomes a detailed explanation of how the lesson should operate.

For the E-3A MPS, the PIDS specified that there should be varying visual aids to the student, based on an instructor selected input. Hence, rules were laid out in order to properly annotate the T.O.s for slides. Additional rules corresponded to maintenance action slides, set-up slides and error slides. Besides annotation, the T.O.s had to be transposed into the CAL. This was accomplished through a set of rules which were taught to the courseware authors These rules were then expanded using computer automation.

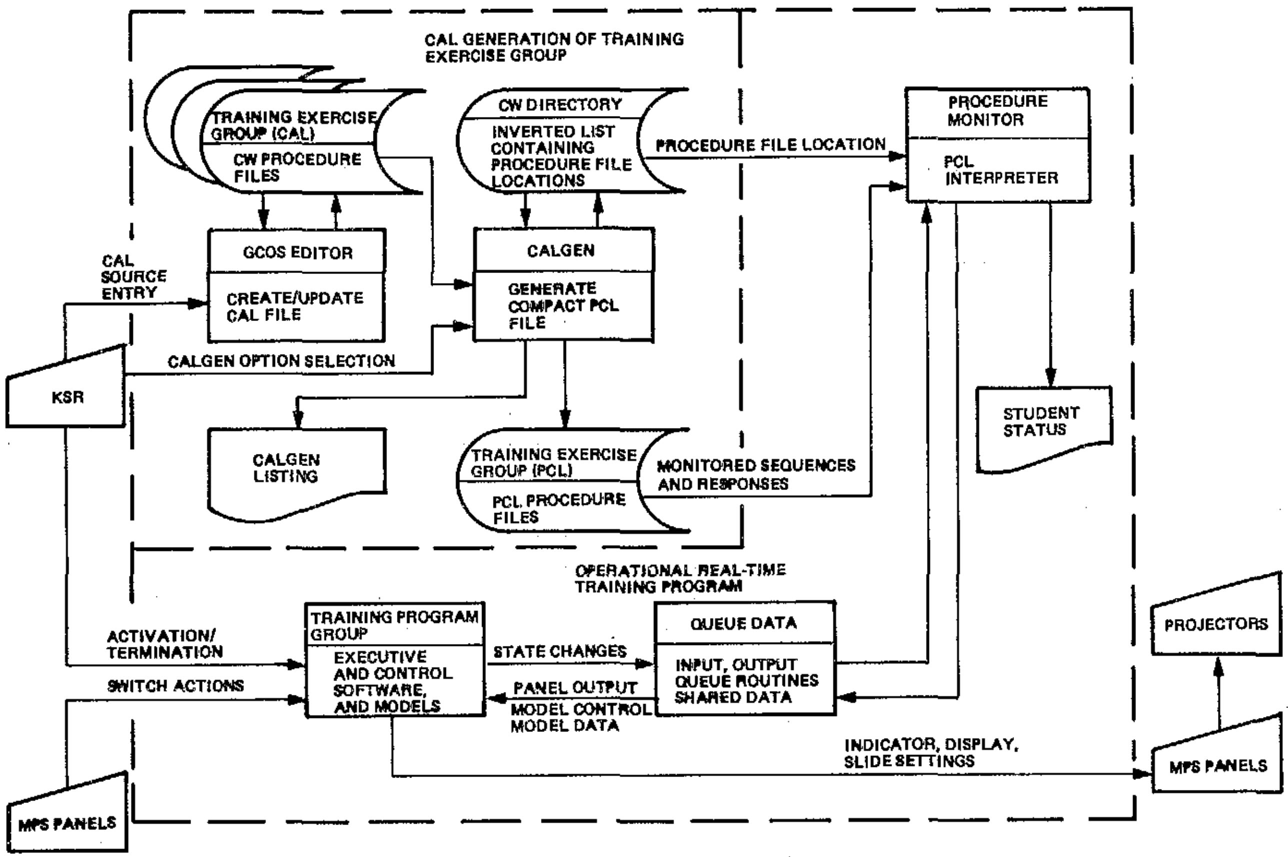


FIGURE 4. E-3A MPS SOFTWARE ARCHITECTURE

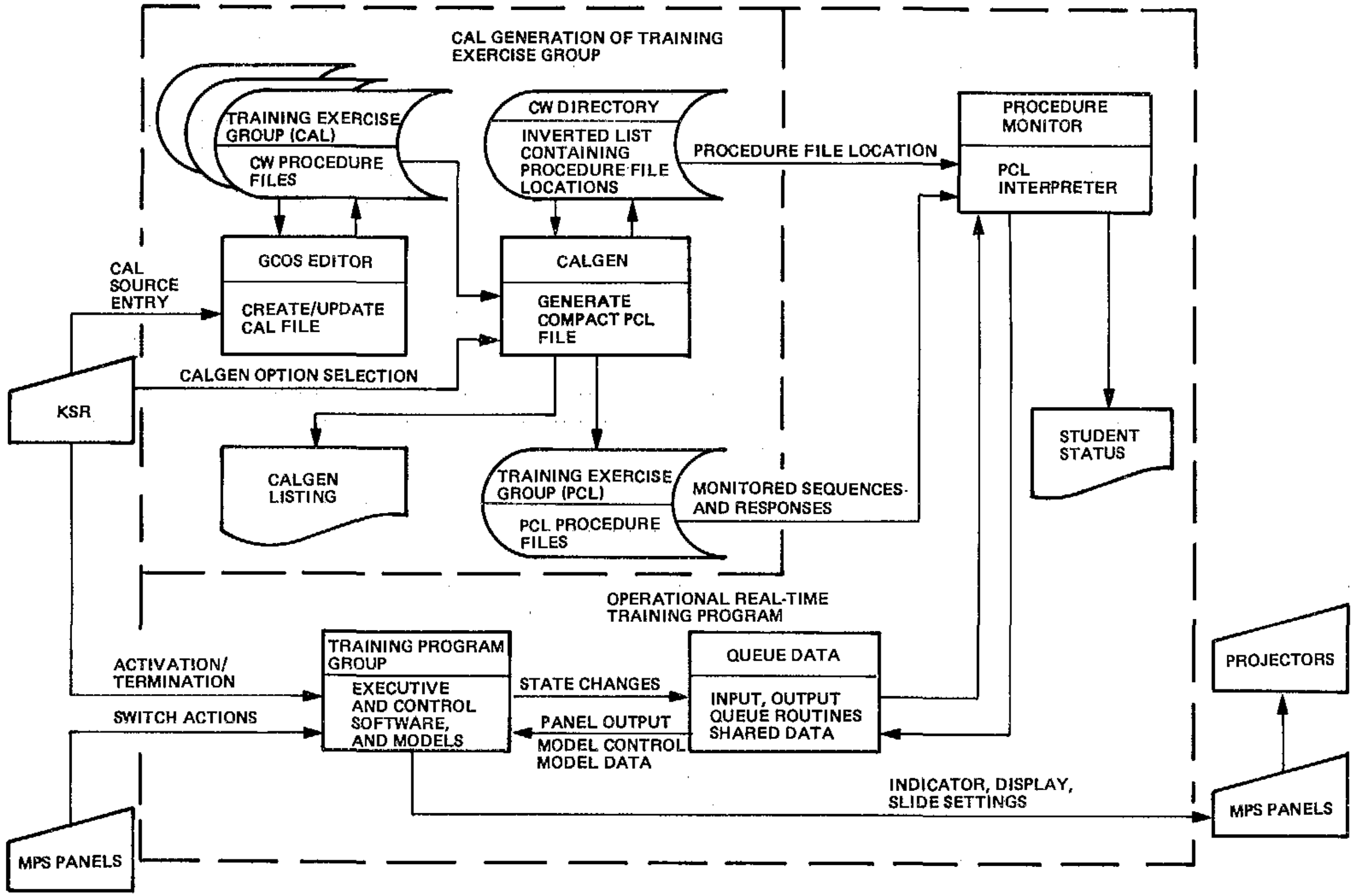


FIGURE 4. E-3A MPS SOFTWARE ARCHITECTURE

The results of this approach to generating the CAL was very satisfactory. The 273 lesson units developed for the E-3A MPS meet their lesson objectives.

The Hardware System

As discussed previously hardware systems for maintenance trainers are relatively simple, making use of off-the-shelf equipment as much as possible. The E-3A MPS is no exception. The E-3A MPS is composed of a Honeywell Level 6 Model 43 minicomputer with 128K of memory, a 10 Mbyte disk, ASR-43 teletype, 2 Mast projectors and various panel components.

A key concept used during the E-3A MPS development was an automated data base defining the possible states of the panel components. The data base listed all inputs and outputs on each panel, type of component, word and bit of each item as read/written to the panels. The data base was used to provide information to the functional groups interfacing with the trainer: software and the digital groups. If a change occured in the hardware, the data base was changed and copies provided to the users. This list was automated and was invaluable in interfacing with the trainer.

Integration

There are two phases of integration for the maintenance trainer. The first integration phase is the conventional software with hardware marriage. The second phase of integration is when the courseware is fully integrated with the software and hardware.

The software integration for the E-3A MPS was more complex in that the courseware interpreter, Procedure Monitor, also had to be integrated. The software integration plan was multi-staged such that both the application software, and the Procedure Monitor was integrated with each other and then with the hardware.

During the software integration, care must be taken to define appropriate tests so that any of the software/courseware interfaces can be exercised. Eventually, all such interfaces are required to be tested.

Courseware integration must be done upon completion of software integration. It involves system functional testing as well as verifying that all lesson units are operational. All functional level testing should be against requirements. Lesson units should be verified through operation of T.O.s, lesson plans or material of that nature. Annotated T.O.s are extremely useful to verify the courseware. During the E-3A MPS courseware integration, we mistakingly used listings to verify the courseware. However, verifying the listing does not mean that the courseware is correct. We eventually used the T.O. and the instructors guide to verify the lesson units.

During system integration of the E-3A MPS it became painfully clear that courseware tools were required for debugging. We produced a courseware debugger, which matured during the E-3A MPS integration phase.

In the future, it is suggested that courseware tools be set up such that courseware testing can be automated to as large a degree as possible. Variability in student response leads to an infinity of parameters to be tested. With at least a minimal amount of automation, high confidence in testing can be achieved.

This is exactly how testing evolved on the E-3A MPS. We eventually used a courseware tool, "virtual student", to verify that each branch of courseware was valid and would operate successfully. We would then verify the lesson unit. If any branch required additional testing we used another tool to start at the correct courseware step. In this manner, with these tools, we were able to complete verification of all lessons and hence, finish system integration.

Conclusions

The conclusions to be drawn about maintainance trainer development from the E-3A MPS experience are presented as follows:

1. Provide robust software architecture able to accomodate changes as well as additional real-time models.
2. Control T.O. annotation or lesson unit generation carefully. Automate the process, to at least allow for interfacing purposes and consistency in documentation.
3. Control PIDs/Proposal to system definition and then through requirements documents. If the specifications are controlled and communicated, the project will procede more smoothly.
4. Test to the PIDS and the T.O.s. Do not test to anything artificial unless agreed upon with the customer.
5. To the largest extent possible, automate testing. Find a point which provides cost effective testing with a reasonable confidence level.

The E-3A MPS has been delivered to Keesler AFB. Three classes have been given, as of July 31, with successful results. The device has been operating without significant maintenance problems for greater than 5000 hours. All software and courseware deficiencies have been corrected under the warrenty provision of the contract. We have remained in close contact with the users and feel that the E-3A MPS represents a successful culmination of our joint efforts.

ABOUT THE AUTHORS

Mr. David L. Winter is a Senior Research Scientist at the American Institutes for Research in the Behavioral Sciences. Mr. Winter has served as project director responsible for design of computer base maintenance procedure simulators to train technicians for the E-3A AWACS Avionics System and participated in preparation of design specifications for the USAF Base and Installation Security System. Mr. Winter holds a B.A. degree from the University of Pittsburgh, a certificate in Russian from Syracuse University, a M.A. degree from Columbia University and a certificate in computer science from the Northeastern University.

Mr. Michael F. Sturm is the E-3A AWACS Engineering Manager for Honeywell, Inc, Training and Control Systems Center. Mr. Sturm has participated in the design and development of various trainers for Honeywell including the FBM Sonar Operational Trainer, the device 21B64, 14E24 PAIR and 14E35 IVDS. Mr. Sturm holds a B.S. degree in mathematics from the Polytechnic Institute of Brooklyn, and a M.S. degree in mathematics from the California State University at Los Angeles.