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Analysis, Design, Implementation, and Deployment of a Prototype Maintenance Advisor Expert System for the MK92 Fire Control System

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Abstract—*In an effort to meet the challenges presented by the fiscal realities of today's defense budget, the Department of Defense (DoD) is seeking to exploit technology that promises to decrease operating costs, while improving operational readiness. Efforts which reduce repair costs, system down time, and the reliance upon outside technical representative are of particular interest. The development of the MK92 Maintenance Advisor Expert System (MK92 MAES) is one such effort. This paper describes the design and development of the MK92 MAES for the diagnosis and repair of the MK92 MOD 2 fire control system deployed on U.S. Navy guided missile frigates. System development is presented in terms of an expert system life cycle model which includes a thorough cost/benefit analysis, a novel approach for knowledge acquisition, an implementation strategy using a visual expert system development environment, and a phased deployment strategy. The system was developed by faculty and graduate students at the Naval Postgraduate School in cooperation with the Naval Warfare Center, Port Hueneme Division.*

1. INTRODUCTION

The 1990s have seen a steady trend of what has been referred to as the "downsizing" of the U.S. armed forces. Along with the resulting reduction in personnel and equipment has emerged an effort to identify technological alternatives that will reduce costs while enhancing operational readiness. Diagnostic expert system technology is one such technology that has the potential to significantly improve operational readiness by ensuring quick and timely repair of defective equipment while minimizing costs associated with unnecessary replacement of good components and obtaining outside technical assistance.

Realizing the great potential of this technology, all three DoD services, Army, Air Force, and Navy, instituted programs for developing and deploying diagnostic expert systems (Ivey, 1992). The Army, for example, initiated in 1990 the development of PRIDE, a diagnostic expert system that aids in the maintenance of the Pulse Acquisition Radar of a HAWK missile battery. The system is now in its third version and is in use by four of the Army's ordinance companies. The Air Force developed and deployed the Expert Missile Maintenance Aid (EMMA) to assist novice munition technicians in isolating faults in missile systems to the lowest replaceable units. The system is currently in use by four Air Force units.

Similarly, the Navy developed a number of diagnostic expert systems over the past several years. One of the first efforts was not a true expert system, but rather an expert system shell, called the Fault Isolation System shell (FIS), that is used to create specific expert systems. One of the first uses of the FIS shell was the development of the Technical Assister System used to diagnose faults in the signal processor of surface ships' sonar systems. Other efforts include the development of an expert system to troubleshoot faults in the AN/USH-32 Signal Data Recorder-Reproducer of the AN/SQR-19 Tactical Towed Array Sonar system and the Phalanx Integrated Diagnostic System (IDS) for diagnosing faults in the MK-15 Close In Weapon System (CIWS), known as the Phalanx, that serves as a surface ship's last defense against antiship missiles. Another highly successful effort by the Navy is an expert system program that develops and deploys a growing number of "expert on a floppy" diagnostic expert systems for a variety of equipments that include boilers, steam plants, air conditioning plants, evaporators, etc.

The development of the MK92 Maintenance Advisor Expert System (MK92 MAES) is another effort to

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improve operational readiness while reducing costs through expert system technology. Developed by the faculty and graduate students of the Naval Postgraduate School in cooperation with system engineers of the Naval Surface Warfare Center, Port Heuneme Division (NSWC-PHD), the objective of the system is to enhance the ability of the MK92 fire control system technicians to better determine, diagnose, and resolve faults occurring in the system.

The MK92 is the designation given to the fire control system (FCS) in operation on the U.S. Navy's *Oliver Hazard Perry* (FFG-7) class of guided missile frigates (FFG) and U.S. Coast Guard medium and high endurance cutters class (WHEC 715-726). Additionally, the system has been deployed on the Australian Adelaide class frigates, Spanish Santa Maria class FFGS, and Taiwan's Cheng Kuh class of guided missile frigate (Sharpe, 1994).

As a fire control system, it is designed to coordinate the detection, tracking and engagement of hostile air and surface targets by the vessel's 76 mm gun and missiles. The MK92 accomplishes this through the use of search/track radars, digital computers, servos, amplidynes, and other components, all largely reflective of 1970s technology. The FCS is modularized to support the maintenance concept of module replacement and the Navy's Planned Maintenance System (PMS), in an effort to minimize the number of personnel required to maintain it.

Maintenance of the MK92 is conducted at the organizational (shipboard) and depot levels. At the shipboard level, Fire Controlmen (FCs) are limited to planned maintenance, fault isolation, and corrective maintenance consisting of replacing modules, circuit cards, and minor Micro-miniature (2M) repair (Lewis, 1993). If more extensive troubleshooting is required, technical representatives must be sent to the ship, no matter where it is, to isolate the problem and correct it. Equipment requiring repair outside the capabilities of a vessel's technicians are turned in to repair depots. All of this translates into increased system down time and higher maintenance costs.

During the period from 1 July 1989 to 30 September 1991, over 40% of all initiated Casualty Reports (CASREPs) requested outside technical assistance in isolating the cause of the failure. Additionally, over 22% of all Depot Level Repairables (DLRs) turned in during fiscal year 1991 were found to be No Fault Evident (NFE), in proper operating condition (Powell, 1993). Faced with a decreasing budget and fewer technical representatives to send to ships, the Navy Surface Warfare Center, Port Hueneme Division (PHD), recognized the need to improve the troubleshooting capability of the shipboard FCs. PHD decided to investigate the possibility of using expert system technology as a possible remedy and approached the Naval Postgraduate School (NPS) in the fall of 1992 for assistance.

This paper describes the development efforts of NPS faculty and students, and PHD engineers. It is organized as follows. Section 2 introduces the cost benefit analysis applied to determine the feasibility of the MK92 MAES project. Section 3 discusses the expert system development cycle of the MAES project. Section 4 takes a closer look at the implementation of the MK92 MAES. Section 5 summarizes the project, discusses lessons learned and provides directions for future efforts needed to field the system. Finally, an appendix provides a brief example of a diagnostic session using the MK92 MAES.

2. COST BENEFIT ANALYSIS

Before commencing the development of the expert system, a cost benefit analysis was undertaken by a NPS graduate student to evaluate the feasibility of the effort. Using CASREP data, NFE information, and other sources of cost related variables, the officer was able to conduct a detailed analysis which looked not only at the costs and benefits as compared to the status quo, but also the sensitivity of changes to various factors and their effect on the economic viability of the project. The following is a brief summary of the study's findings as determined by Powell (1993).

2.1. Assumptions

In order to conduct the cost-benefit analysis, the following set of assumptions was made:

(1) The MK92 MAES will be fielded to 39 ships.
(2) The program life of the system will be until 2005, the anticipated service life of the FFG-7 class.
(3) All quantifiable savings were reduced by a 61% pertinency rate to account for the estimated percentage of casualties in which the MK92 MAES would be useful.
(4) A 50% efficiency rate was applied to all cost savings to account for potential mistakes made by the expert system, as well as to make a more conservative estimate of MK92 MAES' impact.
(5) Net present value calculations used a ten percent discount rate and discounted all cash flows to 1993 dollars.
(6) Personnel costs were computed by accelerating the composite wage rate by 32% to account for leave, medical care, and other fringe benefits.
(7) For purposes of calculating hardward costs, the useful service life of a notebook computer is assumed to be 4 years.

2.2. Benefits

The study found the tangible benefits resulting from the deployment of a maintenance advisor expert system include reduced repair parts costs, manpower savings, reduced mean time to repair, and reduced reliance upon outside technical assistance. In addition, increased operational readiness and improved shipboard training were identified as important intangible benefits. These benefits are detailed below.

2.2.1. Reduced repair parts costs. The use of expert system technology would increase the likelihood of identifying the failed part correctly. Powell's analysis determined that approximately 22% of all Depot Level Repairable parts (DLRs) are perfectly good parts. After applying the conservative efficiency rate of 50% to anticipated savings in terms of unnecessary parts expense, it was determined that $215,748 per year could be saved in terms of parts alone.

2.2.2. Manpower savings. Using expert system technology, onboard technicians would be able to troubleshoot faults much faster than relying on their expertise and outdated technical manuals. Using the Fire Controlman Second Class (E5) Composite Rate, adjusting it for compensation and fringe benefits using a 32% accelerating rate, and reducing potential savings in terms of man-hours by 50%, an annual estimated savings of $118,958 for 39 ships was determined.

2.2.3. Reduced mean time to repair. Since a Navy frigate's weapons systems need to be ready on a moment's notice, a one hundred percent system availability is always the goal. When a casualty does occur, repairs need to be prompt and effective.

The analysis determined the average trouble isolation intensive CASREP required 241 h (over 10 days) in maintenance downtime before the casualty was corrected. It was estimated that the use of the expert system would reduce the downtime associated with casualties within the problem domain by 25%

2.2.4. Reduced reliance upon outside technical assistance. By using the MK92 MAES, a ship would reduce her reliance upon outside technical assistance, thus freeing up the time of the technical experts to focus their efforts on more critical casualties.

The MK92 FCS program manager for Naval Sea Systems Command Pacific determined that 90% of all travel expenditures for fiscal year 1992 were for technical assistance travel. Of the travel expenditures for technical assistance, 85% were made in trouble isolation efforts. After accounting for those in which the MK92 MAES would be useful and applying the 50% factor to provide a conservative estimate, it was determined a savings of $16,926 in travel expenditures by technical representatives could be realized.

2.2.5. Increased operational readiness. An important intangible benefit of deploying the system is the increased operational readiness as a result of the reduction in the mean time to repair. The analysis predicts an 8% increase in fleetwide MK92 MOD 2 FCS operational readiness, based on the estimated 25% reduction of the mean time to repair.

2.2.6. Improved shipboard training and knowledge of MK92 FCS. As FCs work with the MK92 MAES, it is foreseeable they will gain insight as to the thought process and approach an expert takes when troubleshooting a system. In addition, through use of the help features and explanation facility of the system, the FC begins to understand not only what to look for, but how to look for it. He or she could then apply their increased troubleshooting skills to problems outside the domain of the expert system.

The system could also be used as a training tool to diagnose hypothetical casualties. In conjunction with circuit cards which have been intentionally faulted, the MK92 MAES could be used to teach FCs, both on ship and in training schools, effective troubleshooting techniques.

2.3. Costs

The study estimated the following costs for the development of the MK92 MAES: software development and associated labor costs, deployment hardware and commercial software costs, maintenance costs, and training costs. These costs are described in detail in the following sections.

2.3.1. Software development and associated labor costs. Like traditional software development, labor costs make up a majority of the costs associated with expert system development. However, most of the labor costs in an expert system, particularly when using a visual development environment, are associated with knowledge acquisition. Not only must the costs associated with the developers be included, but the cost of the expert's time must be included as well. Table 1 represents the estimated software development costs by fiscal year.

2.3.2. Deployment hardware and commercial software costs. This category included the purchase and fielding of computers with the MK92 MAES. Table 2 lists the costs by computer type, for hardware if fielded to 39 ships.

TABLE 1
Estimated Software Development Costs for the MK92 MAES

Fiscal year	Estimated software development costs
FY 1992	$309,000
FY 1993	$235,000
FY 1994	$335,000

TABLE 2
Estimated Hardware Costs for the MK92 MAES from Powell (1993)

System features	Unit price	Price for 39 ships
386 Monochrome	$1,600	$62,400
486 Monochrome	$1,900	$74,100
486 Passive matrix	$2,600	$101,400
486 Active matrix	$4,000	$156,000

Additional runtime versions of the expert system shell are charged for under the licensing agreement of the tool in use by the MK92 MAES project, therefore only the initial development software need be included in the software costs. Software costs include the purchase of a database program which is to be used to incorporate parts data in the expert system. It is expected equipping 39 ships with a database program will cost approx. $20,500.

2.3.3. Software and hardware maintenance costs. Software maintenance costs include the cost required to report, identify, and implement any changes that may result from trouble reports received from the fleet. Additionally, the effect of ordinance alterations (ORDALTs) on costs must be taken into consideration. It was determined that approx. 75% of a man-year would be required to properly maintain the system. This is estimated to cost approx. $73,850 per year.

In addition to the software maintenance costs, hardware will also need to be replaced or repaired. Hardware maintenance costs are estimated to be approx $12,000 annually.

2.3.4. Training costs. Although the MK92 MAES was envisioned to be user friendly, it was determined a 1 day introduction to the system's capabilities should be given to a ship's FCs at the time of deployment. Total training costs were estimated to be $20,990.

2.4. Economic Analysis

Using present value analysis, savings/investment ratios, and discounted payback analysis, a quantitative approach to determining the economic feasibility of the MK92 MAES approach was accomplished.

2.4.1. Present value analysis. Present value analysis was accomplished by comparing the present value cost of developing, fielding, and maintaining the MK92 MAES against that of the status quo. Table 3 represents the present value calculations with the monochrome 486 monitor chosen for hardware implementation. The status quo's present value cost was determined to be $7,868,422. The fielding of the MK92 MAES through 2005 was determined to have a Net Present Cost of $6,822,201. This represented a potential net present savings of $1,046,221.

TABLE 3
Present Value With Monochrome 486 from Powell (1993)

Alternative	Net present value
Status quo	$7,868,422
MK92 MAES	$6,822,201
Savings	$19,046,221

2.4.2. Savings/investment ratio. Savings/investment ratio (SIR) is the relationship between future cost savings and the investment necessary to obtain those savings. If the SIR is equal to or less than one, the decision to make an investment should not be made on an economic basis alone. The SIR for implementation of the MK92 MAES varied from 3.033 using a 486 with a monochrome screen to 2.617 using a 486 with an active matrix color screen, indicating its implementation and deployment is a sound economic decision. Table 4 lists the expected SIRs by computer type.

2.4.3. Discounted payback analysis. With discounted payback analysis, the shorter the payback, the more desirable the project. The discounted payback for the MK92 MAES project was determined to be four years beyond fielding of the system.

2.4.4. Sensitivity analysis. Due to the inherently uncertain application of economic analysis, a sensitivity analysis was conducted in an effort to anticipate the effect changes to policy and economic factors would have upon the feasibility of the project. The following factors were considered in the application of sensitivity analysis:

- *Accelerated decommissioning.* Assuming all other variables remained constant, it was determined the MK92 MAES had to be deployed on 20 ships to breakeven.
- *Cumulative dollar value of all savings realized.* It was determined that even if program savings were overestimated by 45%, economic analysis would still be in favor of fielding the MK92 MAES.
- *Sensitivity of repair parts savings.* It was

TABLE 4
Summary of Savings/Investment Ratios (SIRs) by Computer Option from Powell (1993)

Computer	SIR
386 Monochrome	3.104
486 Monochrome	3.033
486 Passive matrix	2.881
486 Active matrix	2.617

determined, all other variables remaining constant, that repair part savings could be reduced by 74% before breakeven would be reached.

- *Trouble isolation man-hour savings.* All other variables remaining constant, if no man hour savings were realized from deployment of the MK92 MAES, the system would still be preferable to the status quo.
- *Technical representative travel savings.* Regardless of the impact of the MK92 MAES on travel savings, its deployment would still be preferable to the status quo.
- *Project delay.* The study determined, even if delayed by one year, the Navy would still receive $755,063 in discounted savings from MK92 MAES deployment.

As a result of these findings, the decision was made to proceed with the development of the expert system.

3. EXPERT SYSTEM DEVELOPMENT CYCLE

This section discusses the expert system life cycle used to develop the MK92 MAES.

3.1. Expert System Life Cycle Model

The expert system life cycle (ESLC) model used by the MK92 MAES development team is a variation on the model presented by Prerau (1990). Prerau segments the ESLC into three phases; the initial phase, core development phase, and final development and deployment phase.

The initial phase involves obtaining management approval, project team formation, domain selection, and hardware/software selection. These steps lay the foundation for the development process.

Core development includes an assessment of the project's feasibility and the implementation of a full prototype. Full prototype implementation includes knowledge acquisition, representation, and implementation.

Final development and deployment mark the final stage in Preran's ESLC model. It is at this point the development team builds a final production system. The system is tested, evaluated, and known errors are corrected.

3.2. Problem Selection

As pointed out by Walters & Nielsen (1988), a broad problem domain can lead to ambiguity and a lack of direction for the development effort. As a result, designers of an application fall into the trap of designing a system which will attempt to do everything; the end result being an expert system which does nothing well.

To avoid this trap, it was important to define a bounded problem for the MK92 FCS domain to which the domain experts could construct a logical approach to its troubleshooting. In consultation with NPS faculty, PHD determined an expert system designed to diagnose problems associated with the Daily System Operability Test (DSOT) would be the best candidate for the initial effort.

The DSOT is a daily evaluation of a U.S. Navy combatant's weapon systems, from the fire control radars to the weapons themselves. It provides a rapid and comprehensive means of assessing the availability of the ship's combat suite. In the process of conducting the DSOT, sailors inject simulated targets to evaluate the response of their fire control system and associated weapons against established standards. As a result, a hard copy summary of system functional performance is provided to the operator indicating any faults with the system.

Three primary areas are the focus of the DSOT. These are CAS/STIR transmitter RF Power Checks; DSOT initialization and calibration; and the performance test. Figure 1 represents the three primary areas of DSOT. The RF Power checks are conducted to ensure minimum required power is available to system components. DSOT initialization and calibration, as the name alludes, is the phase in which the calibration of the MK92 FCS' fire control channels takes place. As each channel is tested in sequence, the system issues GO/NOGO status identifiers which are printed out each time DSOT is run. These GO/NOGOs flags are used by system maintainers as starting points in the troubleshooting process. During the Performance Test, simulated targets are introduced into the system which the system attempts to detect, track, and engage. As with the DSOT Calibration test, a series of GO/NOGOs are printed out. Any time the system falls outside established parameters, a NOGO is issued. Similarly, the printout serves as a starting point for the FCs diagnosing the problem.

Because the GO/NOGO output format of the DSOT is the primary indicator of a system fault, it was an ideal candidate for selection as a domain boundary. Furthermore, as the DSOT output is the usual starting point for FCs troubleshooting the system, it would be a logical input to the proposed Maintenance Advisor Expert System.

3.3. Development Team

3.3.1. Domain experts. Once the problem domain was identified, the next task became that of establishing the

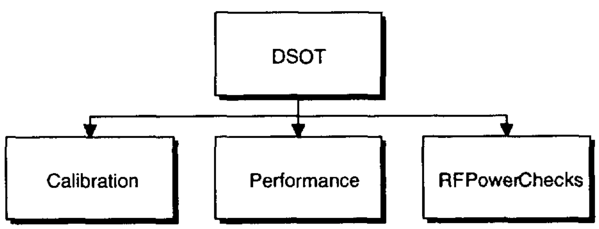

FIGURE 1. DSOT Modules.

development team members. As the engineers at NSWC Port Hueneme were intimately familiar with the expertise of the various technical representatives for the MK92 FCS, they were tasked with identifying the best candidates for the domain experts. Their selection included one primary domain expert, a technical representative under contract to the U.S. Navy from UNISYS with almost 35 years of experience, and a secondary expert, an NSWC engineer with 18 years of MK92 experience. Both have extensive experience in all aspects of diagnosing casualties to the MK92 MOD 2 and were enthusiastic about contributing their time and knowledge in developing the expert system.

3.3.2. Knowledge engineers. The original intent was to train and use Master Thesis officer students from the Naval Postgraduate school as knowledge engineers during the knowledge acquisition phase. However, because the chosen form of representation, procedural networks, matched very closely the knowledge structure of the problem domain, the intermediary of knowledge engineers was not required. As detailed in a later section, the domain expert was able to represent his knowledge directly in a form suitable for implementation without the assistance of knowledge engineers. In so doing, the traditional bottleneck created by an iterative interview process was substantially decreased. This was particularly important given the geographic distance of the developers and domain experts, and resulted in a smoother implementation effort.

3.3.3. Expert system programmers. Though not involved directly in knowledge acquisition, the NPS graduate students were responsible, under the guidance of NPS faculty, for the design and implementation of the expert system in the selected development shell. In addition to coding, they conducted verification, validation, and testing. Additionally, they assessed the impact of changes to both schedule and budget, as well as other aspects of program management.

3.4. Knowledge Acquisition

The process of capturing domain knowledge was accomplished through several means.

3.4.1. Expertise of experts. The primary source of knowledge was from the domain experts. With over 50 years of cumulative experience in fire control system diagnostics, mostly on the MK92 MOD 2 FCS, they were able to provide expertise and insight to troubleshooting which could not be obtained through examination of technical manuals alone. Their knowledge provided the heuristics on which much of the expert system was based.

3.4.2. Technical manuals. Technical manuals supplemented the expert's knowledge, providing a resource to which they could refer to when documenting their expertise. The manuals, however, had to be used with caution. In some instances, they were inaccurate, requiring careful scrutiny by domain experts and other PHD engineers. Fortunately, the extensive experience of the domain experts enabled them to recognize areas in which the technical manuals were inaccurate. In such cases, the engineers would consult other experts, or if necessary, consult manufacturers of specific components for additional information.

3.4.3. Other recorded sources of knowledge. In addition to the domain expert's knowledge and technical manuals, information from other sources was used. One such source was Casualty Reports (CASREPs) requesting technical assistance. CASREPs include symptoms of a casualty, its cause, and corrective action taken.

Another source used was Ordinance Alterations (ORDALTs). ORDALTs are changes made to a weapons system such as the MK92 FCS or a missile system. Included in these changes is a detailed documentation which has not been incorporated in the technical manuals. ORDALTs provided a useful and more timely supplemental source of knowledge than the technical manuals.

3.4.4. The knowledge acquisition methodology. Traditional knowledge acquisition techniques comprise an iterative process that consists of interviewing, eliciting the domain expert's knowledge, and testing that knowledge. This process requires close, repetitive interaction with the domain expert, creating a bottleneck in the development process. Additionally, such problems as interviewer bias, communication errors, and other anomalies can distort the expert's knowledge.

To enhance the knowledge acquisition process, the MK92 project team decided to illicit the domain experts knowledge by asking them to develop graphical diagnostic trees of the system's components. Diagnostic expert systems lend themselves well to this type of knowledge acquisition. Troubleshooting frequently requires following one or more paths of a hierarchical diagnostic tree. By using a diagnostic tree formalism, the experts were able to graphically represent their knowledge and review this knowledge for accuracy, thereby reducing the number of iterations in the knowledge acquisition task.

Figure 2 is an example of a diagnostic tree developed by the PHD engineers. As Fig. 2 demonstrates, the diagnostic trees represent a series of hierarchical questions which an expert would normally follow when diagnosing a problem. As the FC answers each question, he or she traces the thought process of the domain expert. Although yes/no questions are the most common type of

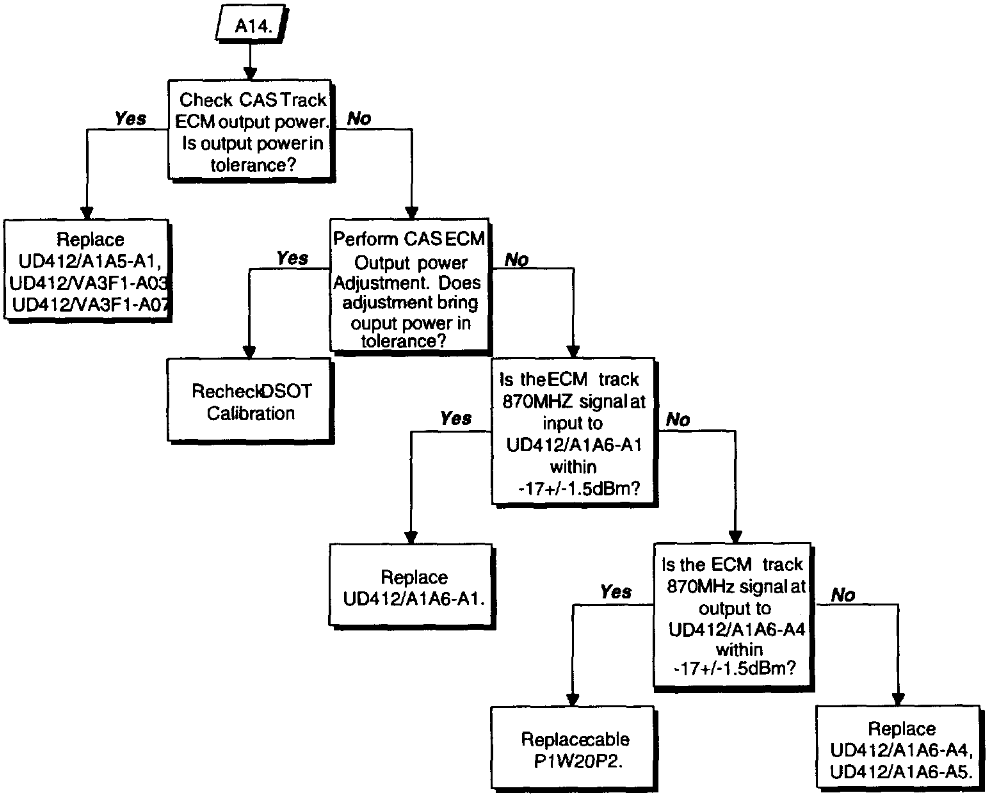

FIGURE 2. Example of a MK92 MAES Diagnostic Tree.

questions asked, case statements could also be used to elicit one out of several responses.

The approach to knowledge acquisition involved developing a strategy for modularizing the problem domain. By breaking the problem area into modules, the domain expert could more easily concentrate on identifying the symptoms and troubleshooting procedures of a specific segment of the MK92 MOD 2 FCS.

The first level of abstraction was to segment the problem into calibration, performance, and RF Power check modules, as these were separate subjects of the DSOT procedure with separate GO/NOGO output and parameters.

Once the main modules were identified, the next task was to divide each module into logical groupings in which similar symptoms, as evidenced by test output, would occur. To accomplish this, the domain experts began by identifying the instances of NOGO readings and grouping them according to potential cause.

First, a grouping was made according to which component the symptom (a NOGO) was identified. For instance, there are two primary radar components, CAS and STIR. Symptoms were identified according to whether they affected the CAS alone, STIR alone, or both.

Another level of abstraction is related to the mode of the radar in which the failure occurred. Modes include track mode and search mode, Electronic Counter-Measures (ECM), and others. If for example the symptom was a NOGO in the CAS portion of a test of the fire control system, but only in search mode of operation, a diagnostic tree would be created that would graphically depict the procedure for identifying the cause of the problem. This procedure of breaking the knowledge into levels of different abstraction in a hierarchical structure enabled the domain expert to lay out and refine their troubleshooting strategy.

3.5. Knowledge Representation

In addition to knowledge acquisition methodology decisions, it was important to determine the method of knowledge representation. The challenge of knowledge representation lies in identifying a method which accurately depicts the expertise of the domain expert in such a way as to facilitate the knowledge coding process.

A rule-based paradigm was initially considered as the knowledge representation method of choice. It was noted, however, that a rule-based system is by premise a nonprocedural form of representation while the knowledge of this particular domain is highly procedural. Representing procedural information using a rule-base system results in several problems. First, many more rules are required to represent the knowledge. Second, sequencing, which is a characteristic of procedural knowledge, is much more difficult to perceive in a rule system, making development and debugging more difficult. Third, maintenance becomes a more error-prone process. As new rules are added, the sequence-dependent characteristics embedded in the rule may be affected in unpredictable ways (Walters & Nielsen, 1988).

A more flexible method of knowledge representation, the procedural network, was considered and ultimately selected as the knowledge representation method. Procedural networks, like flow charts, are graphical representations of the conditions which must exist before a conclusion can be reached. Each procedure is linked, defining the flow of logic within the network. Within each procedure is a series of instructions which are "executed", providing a vehicle for forward and backward chaining. Figure 2 is a sample procedural network that represents troubleshooting of a part of the system.

A main advantage of using procedural networks as a representation scheme for this application domain is its close match with the approach used by experts in diagnosing and resolving problems. In addition, procedural networks, are inherently modular. These two characteristics mirror the knowledge acquisition approach of the domain expert. As will be demonstrated in the following sections, the modularity and structure of procedural networks allowed for easy mapping from representation to implementation.

3.6. Knowledge Coding

The modular approach to building the knowledge base carried over to the knowledge coding process. As domain expert knowledge was acquired and knowledge modules were completed, the implementation team began the task of mapping the knowledge as represented by the diagnostic trees to the expert system shell.

As with the representation scheme, the suitability of the selected tool to the type of knowledge being captured was a key consideration for the NPS developers. Prior to NPS' involvement in the project, unsuccessful attempts were made at implementing the acquired knowledge in an expert system shell that did not lend itself well to procedure-based knowledge representation. Several expert system shells were evaluated for their compatibility with the procedural knowledge of the MK92 MAES, and the expert system shell Adept, by Softsell, was selected (Lewis, 1993).

Adept is a visual expert system development tool which incorporates a graphical user interface (GUI) builder for the Microsoft Windows environment. Designed specifically for diagnostic expert system development, Adept implements knowledge as a collection of procedures, which are linked together to form a procedural network.

Figure 3 is an example of the implementation of the knowledge obtained from the domain expert, shown in Fig. 2. A comparison of Fig. 2 with Fig. 3 reveals the ease with which knowledge is mapped from the diagnostic trees, as represented by the experts, to the expert system shell. This close affinity between representation and implementation greatly enhanced the testing, validation, verification, and modification of the system.

To ease implementation of the domain expert's knowledge, the diagnostic trees were broken down into modules which represented the paths the domain expert would follow in his diagnosis (Smith, 1994). Each module was then implemented as a procedure in Adept. By maintaining correspondence wherever possible between the problem domain, diagnostic trees, and their

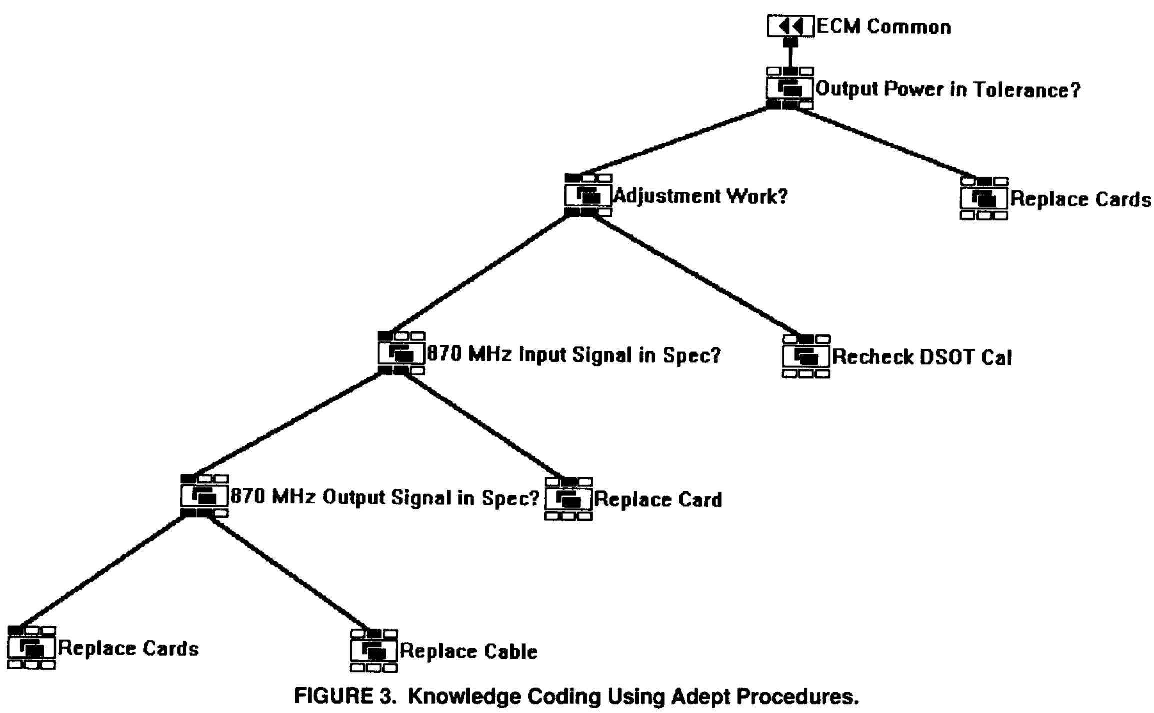

FIGURE 3. Knowledge Coding Using Adept Procedures.

implementation, the ability to perform maintenance and verification are enhanced.

3.7. Knowledge Verification and Validation

An important aspect of the expert system development cycle for this project was verification and validation of the knowledge. Verification plans were prepared to ensure that the domain expert's knowledge was accurate and complete while validation plans were designed to ensure the implemented procedures accurately represented the knowledge provided by the experts.

Independent verification of the knowledge was conducted by another domain expert at NSWC with 20 years of experience in the MK92 FCS. The independent expert was responsible for evaluating the knowledge, identifying any discrepancies, and signing off on knowledge he certified as accurate.

Once the knowledge was verified, validation of the expert system was conducted by NPS graduate students and involved the comparison of the knowledge document with the corresponding expert system code. Five categories of errors were identified: domain expert logic errors, spelling errors, programmer transcription errors, programmer interpretation errors, and programmer logic errors. Completed expert system modules were then sent to the domain expert for further evaluation. Discrepancies that were identified by the domain expert were recorded on trouble reports and returned to NPS personnel for correction.

In both verification and validation, the ability to trace the knowledge as represented by the diagnostic trees to the actual code proved to play a key factor in establishing an effective verification and validation process. The verification and validation team was able to quickly and easily verify and validate the operation of the MK92 MAES against the domain expert's knowledge. We believe that the logical representation of the domain experts knowledge and its ability to map easily to the implementation, as a comparison between Figs 2 and 3 would indicate, made the verification and validation process faster, easier, and consequently less costly than if it were applied to systems developed using traditional programming environments.

4. EXPERT SYSTEM IMPLEMENTATION

4.1. Test and Evaluation

Testing is the process in which the operation and behavior of the expert system is evaluated through the use of test cases (Dills & Tutt, 1994). Although the knowledge has been certified to be correct, as discussed in Section 3.7, and the implementation was determined to be representative of the knowledge base, it was still necessary to determine whether or not the expert system functioned as intended.

Before the system could be fielded, a test and evaluation plan had to be established. To maximize the use of available resources, a test plan was developed which prioritized the order in which testing was to be completed. To accomplish this, MK92 MAES project team members examined CASREP information to identify high failure, high cost components which could be diagnosed by the expert system. Additionally, they attempted to maximize the number of diagnostic paths a particular test case would evaluate (Dills & Tutt, 1994).

Working with fleet technicians at both Fleet Training Center Pacific (FLTRACENPAC) and Port Hueneme, NPS personnel established a testing order which would test the parts identified through CASREP analysis and path tracing in an order which was as convenient as possible for those conducting the evaluation. The test cases were implemented by both FLTRACENPAC and personnel operating a shore based mock-up of the MK92 MOD 2 FCS in Port Hueneme (Dills & Tutt, 1994).

Test deficiencies were provided on verification sheets, denoting any problems encountered. Those identified were first evaluated by the knowledge coders, to ensure an error in implementation was not made, with the remaining problems passed to the domain expert for evaluation. Test cases are currently being executed.

4.2. System Deployment

Before the system was deployed, considerable effort was expended to demonstrate the system to fleet sailors. Visits to ships on the waterfront, presentations at navy-wide technology expositions, and demonstrations at Navy training commands were used to gauge enthusiasm for the product as well as gain further insight as to deployment issues. Questions regarding the type of computer to be deployed (desktop vs laptop), what commands to receive evaluation copies, and suggestions for enhancements were sought.

To demonstrate the capability of the system in an effort to sustain management support for the project, it was determined the system would be deployed in phases. The first phase would consist of the first two modules; calibration and performance. Power checks would be developed and fielded based upon the success of the first two. In so doing, the system could serve as a proof of concept while at the same time minimizing economic risk by initiating further development.

The decision was made, after an evaluation of alternatives, to provide a copy of the expert system to a frigate preparing to deploy, the *USS Sides* (FFG-14). Other evaluation copies were provided to the Navy's MK92 FCS training school. Briefings were conducted with all levels of shipboard management, from the commanding officer to the actual technicians who would be using the system. The system was deployed on a commercial off the shelf (COTS) notebook computer which allows the FC to take the expert system to the location of the casualty.

Initial feedback has been very positive. Upon returning from her deployment, *USS Sides* sent a message to her chain of command in which the *USS Sides* stated its evaluation of the MK92 MAES. The *USS Sides* (1995) noted, "MAES correctly diagnosed and recommended the proper corrective action for all faults" which were within the domain of the expert system. By their estimates, during a 3 month deployment, the MK92 MAES saved 30 man-hours in troubleshooting and provided over 40 man-hours of training. Their confidence in the MK92 MAES led them to recommend further testing of the system be carried out and implementation be considered for all MK92 MOD 2 frigates (*USS Sides*, 1995).

In addition to its deployment in *USS Sides* (FFG-14), the MK92 MAES was used to troubleshoot a casualty onboard *USS John A. Moore* (FFG-19). *USS John A. Moore* was receiving a technical assistance visit by NSWC engineers during a port visit to NSWC Port Hueneme, CA. The ship was experiencing a casualty which was resulting in NOGOs for all readings in the calibration portion of the DSOT. Ship's force had been troubleshooting the casualty for approximately one week (Torres et al., 1995). Using the MK92 MAES, NSWC engineers and *USS John A. Moore* FCs were able to successfully isolate the problem in approx. 15 min (Seto, 1995).

5. SUMMARY, CONCLUSIONS AND FUTURE WORK

The MK92 MAES represents a proof of concept in diagnostic expert systems and their role in the U.S. Navy. With the potential for significant savings in terms of dollars, and time, the MAES promises to provide sailors with a diagnostic tool which can alleviate their need to rely upon outside assistance. The result is an improvement in combat readiness, reduced repair parts costs, manpower savings, reduced dependence upon outside technical assistance, and enhanced training .

The use of diagnostic trees and a visual expert system development environment eased the processes of knowledge acquisition, representation, and coding. The procedural structure and intuitive representation in both the diagnostic trees and expert system shell represent an instance where due consideration was given to matching the knowledge representation and implementation to the problem domain. The result was a modular system which provided for easier maintenance and evolution.

Though further testing and evaluation has yet to be done, all indications are that expert systems have matured to the point they can play a role in the everyday activities of the sailor. As budgets decrease, and personnel depart, the need to capture the knowledge of the Navy's "experts" increases. The MK92 MAES represents one such effort to move expert systems out of universities and laboratories and onto the "front lines".

Much remains to be done to transition from the current working prototype to a full production system. This includes augmenting and refining existing knowledge, comprehensive testing, validation, and verification of the knowledge, evaluating the usefulness, user friendliness, reliability of the systems, expanding the scope to the system to include expertise for troubleshooting all components of DSOT and other problematic areas of the system, analyzing implementation alternatives aboard ships, assessing the system's value as a training aid, and developing a life cycle support for the system.

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APPENDIX

The following is an example of a troubleshooting session using the MK92 MAES prototype.

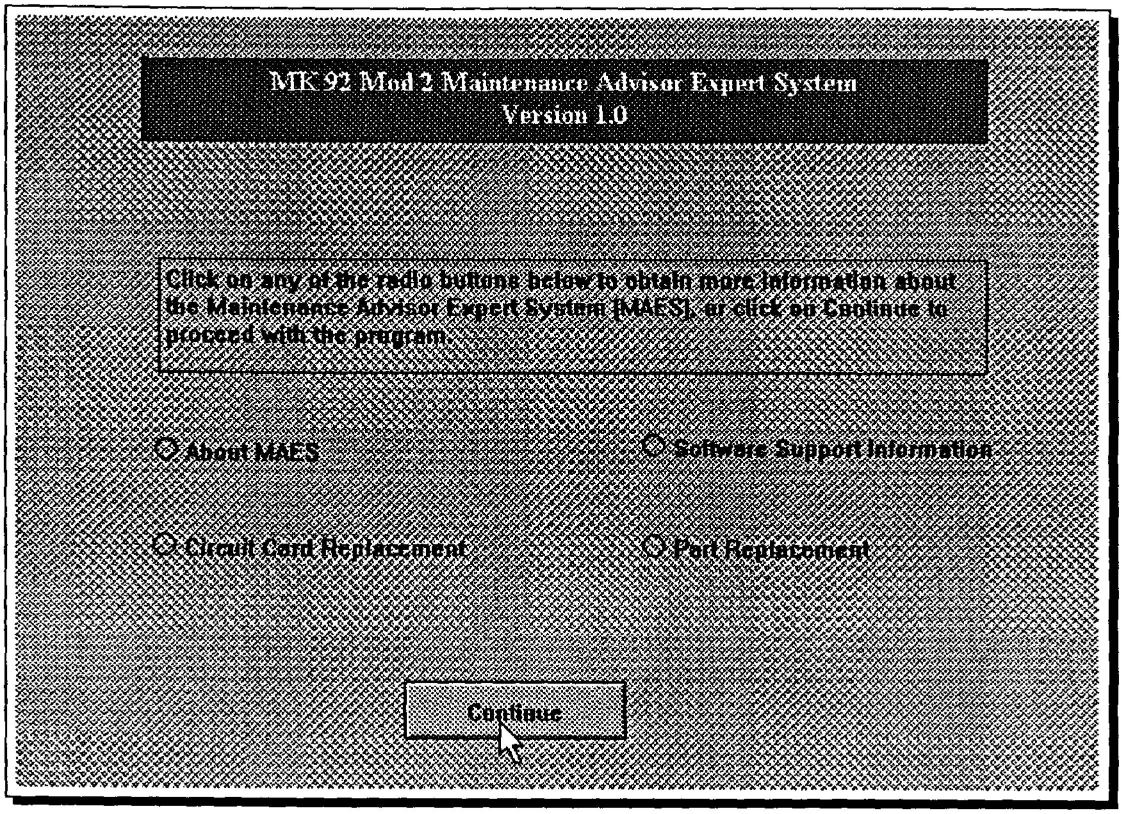

FIGURE A1. MK92 MAES Start-up Screen.

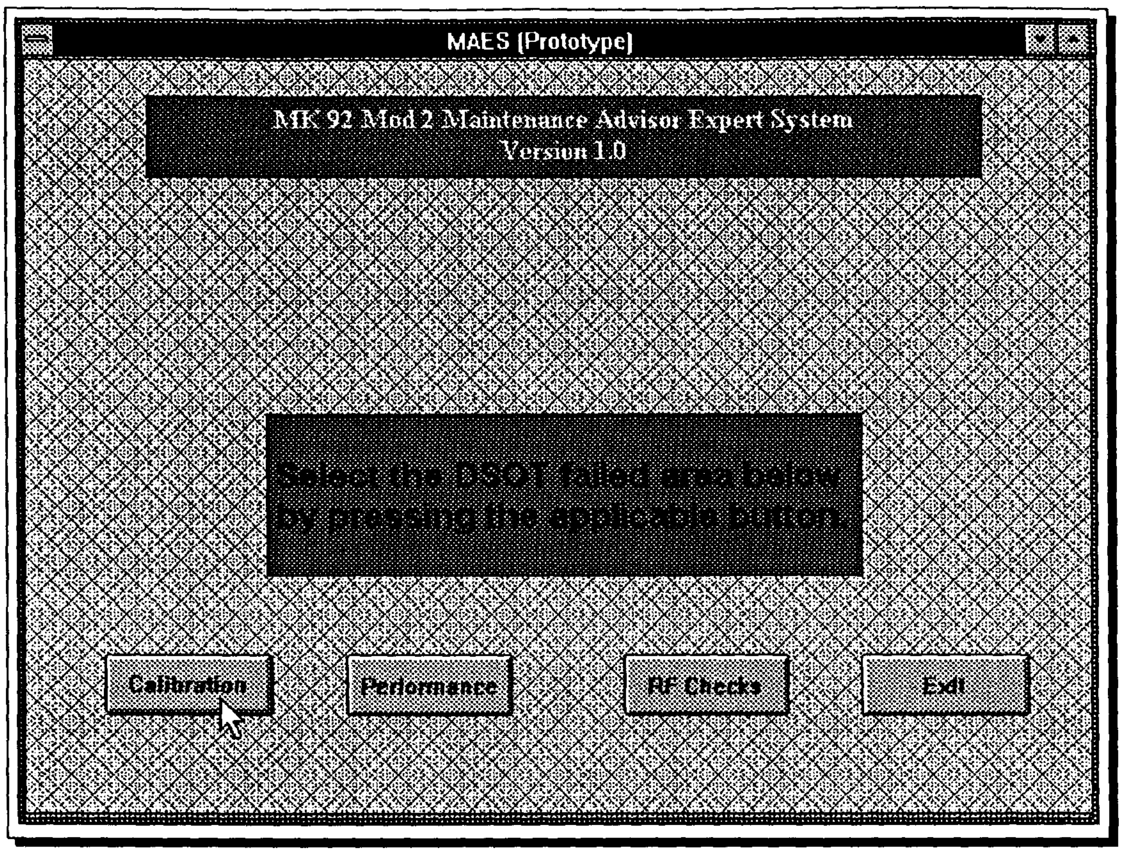

FIGURE A2. DSOT Failure Selection Screen.

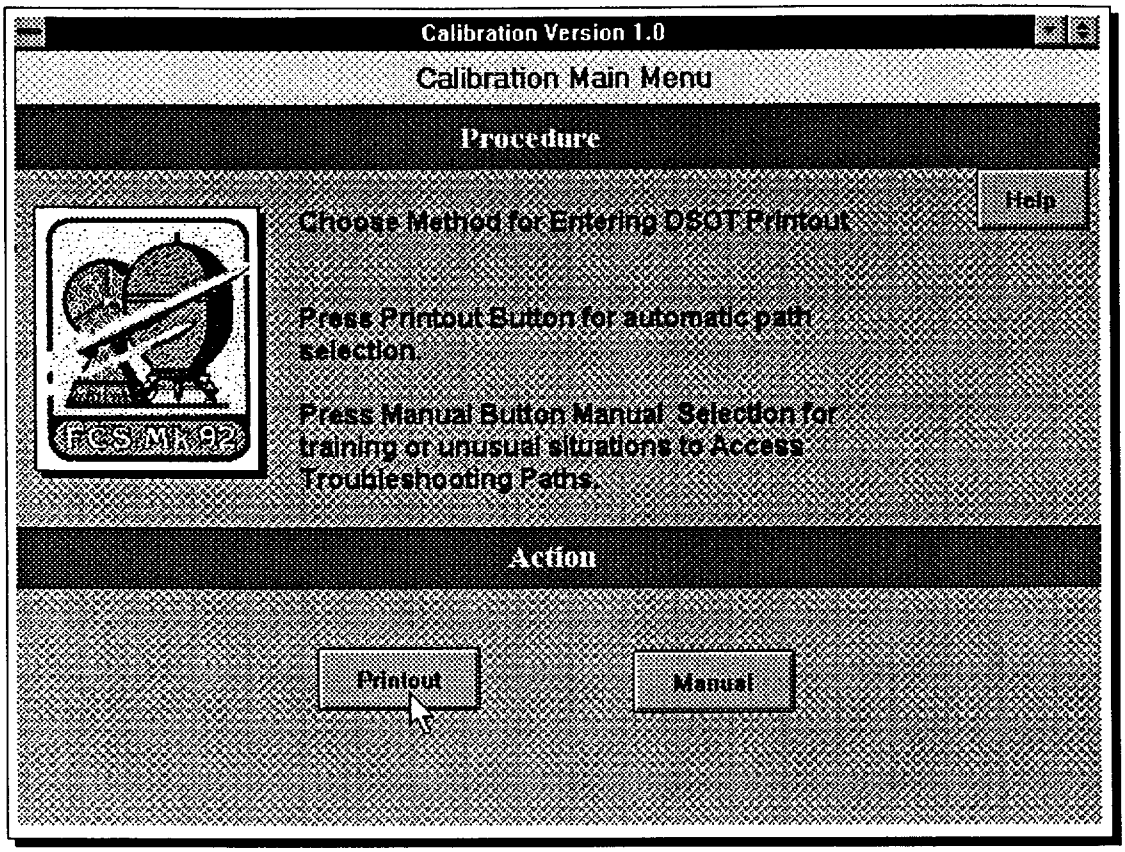

FIGURE A3. Troubleshooting Method Selection Screen.

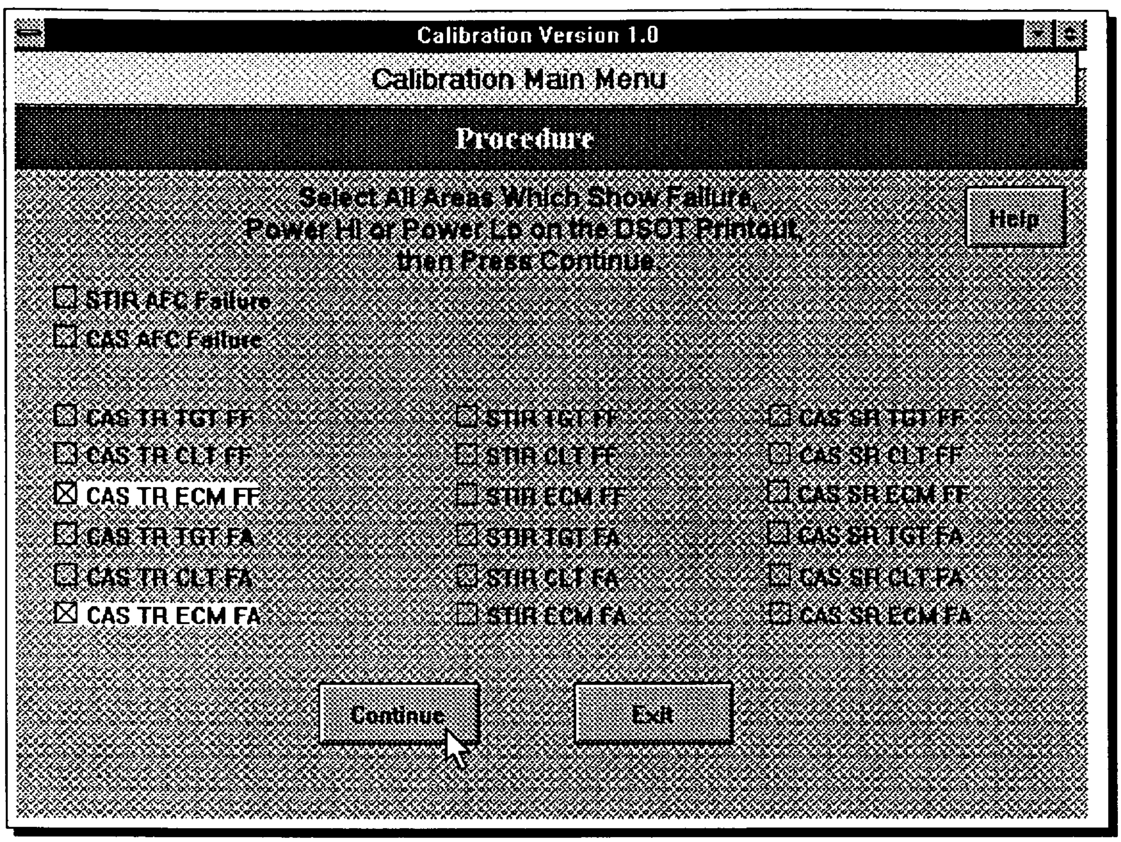

FIGURE A4. MK92 MAES DSOT Printout Display Screen.

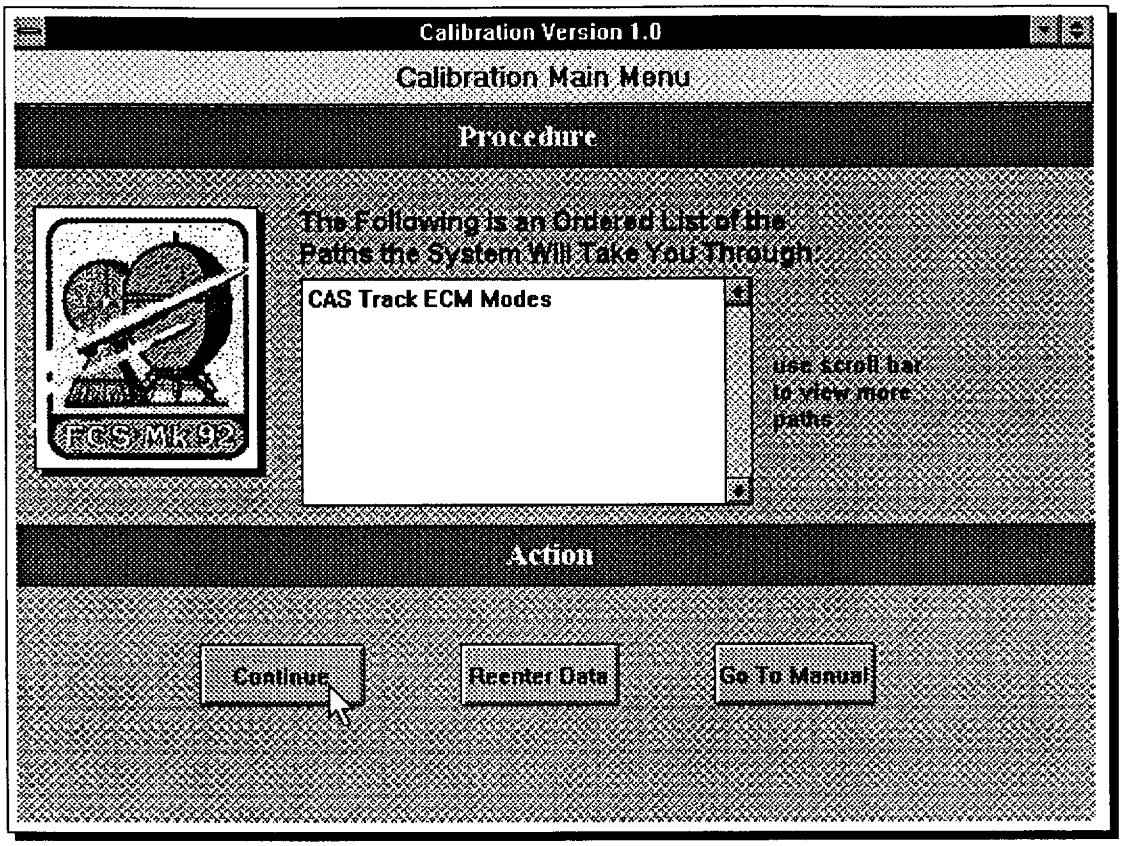

FIGURE A5. MK92 MAES Diagnostic Path Display Screen.

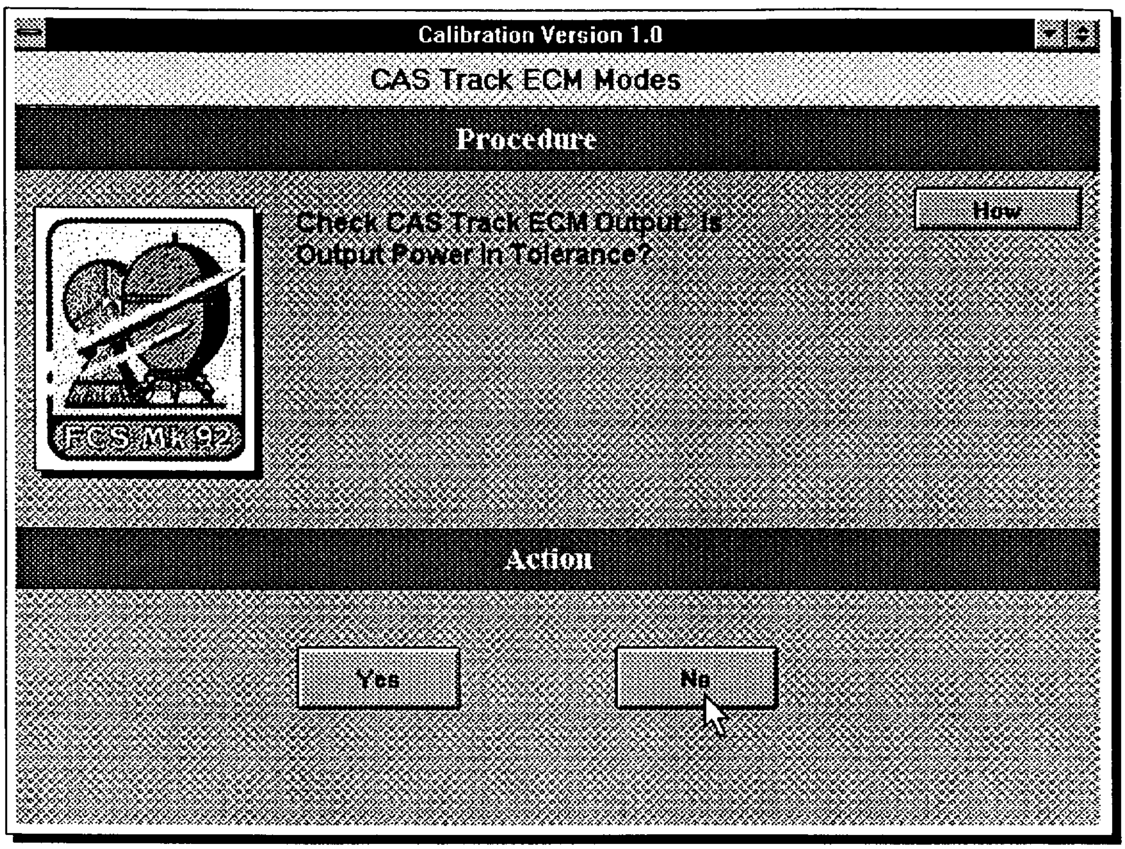

FIGURE A6. Output Power Diagnostic Screen.

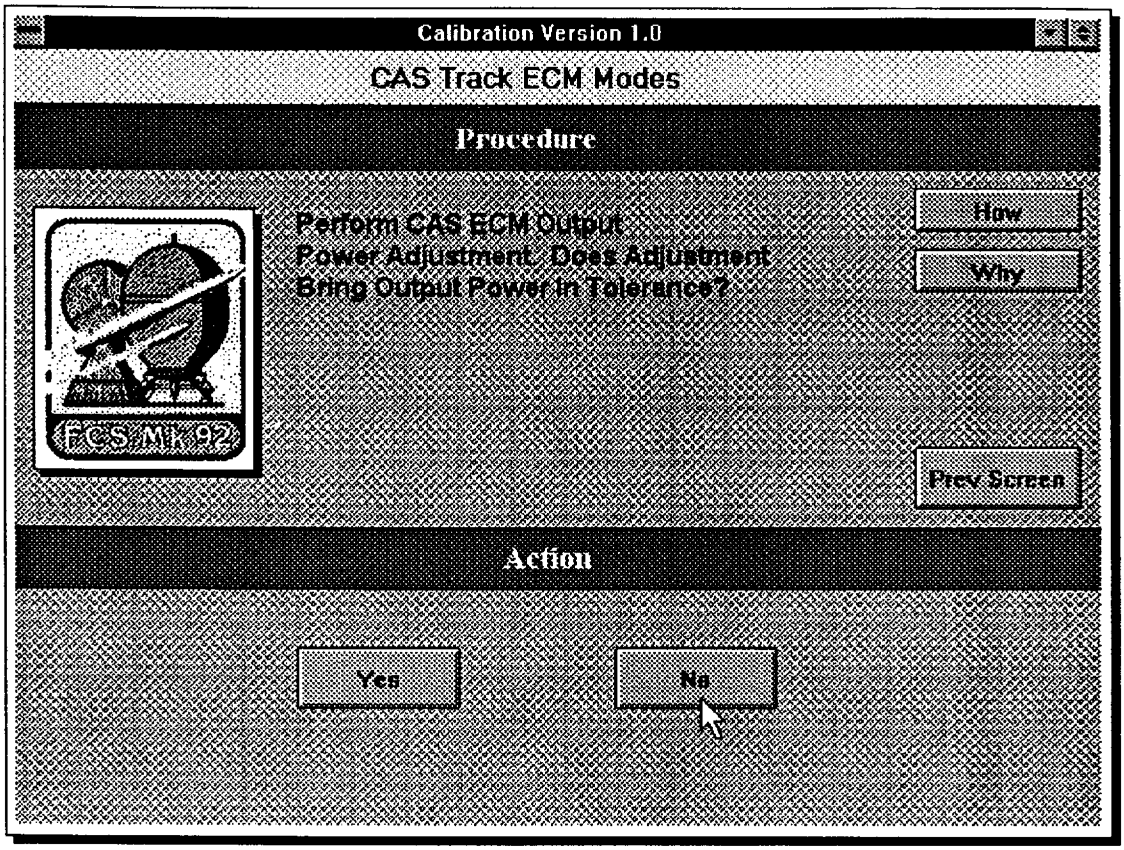

FIGURE A7. Output Power Adjustment Diagnostic Screen.

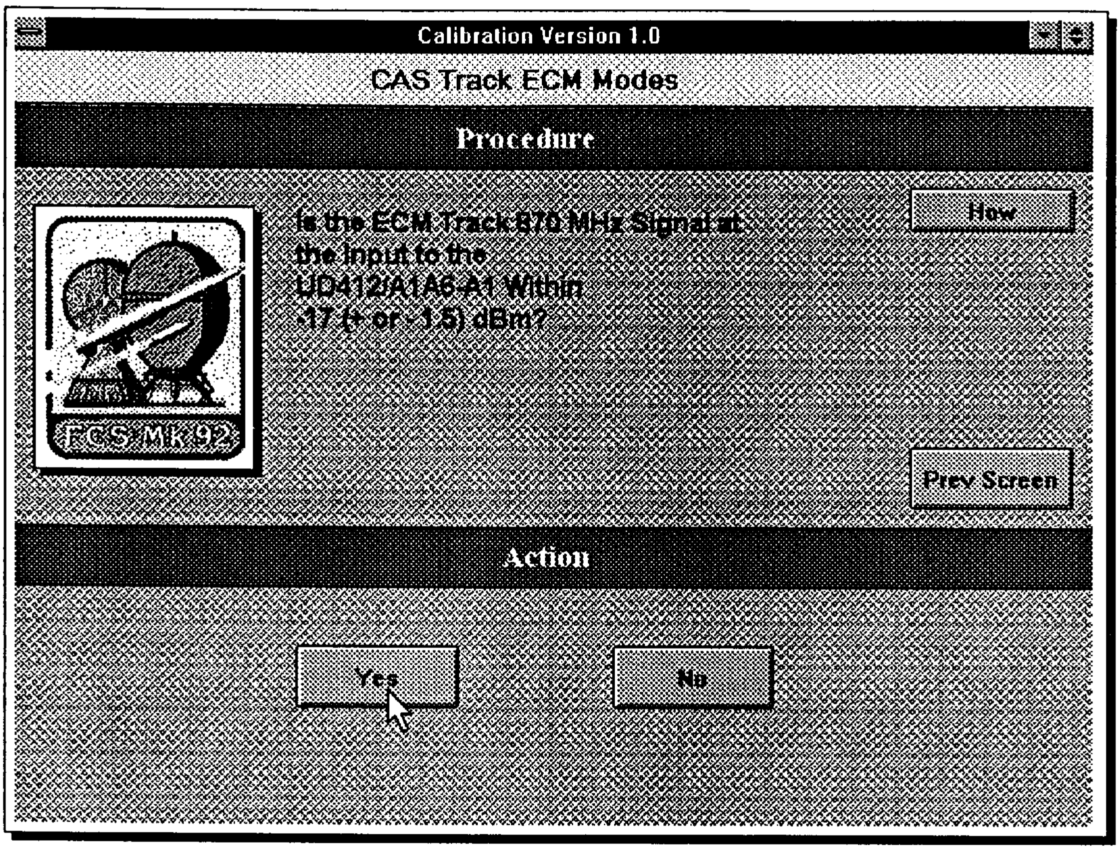

FIGURE A8. ECM Track 870 MHz Signal Diagnostic Screen.

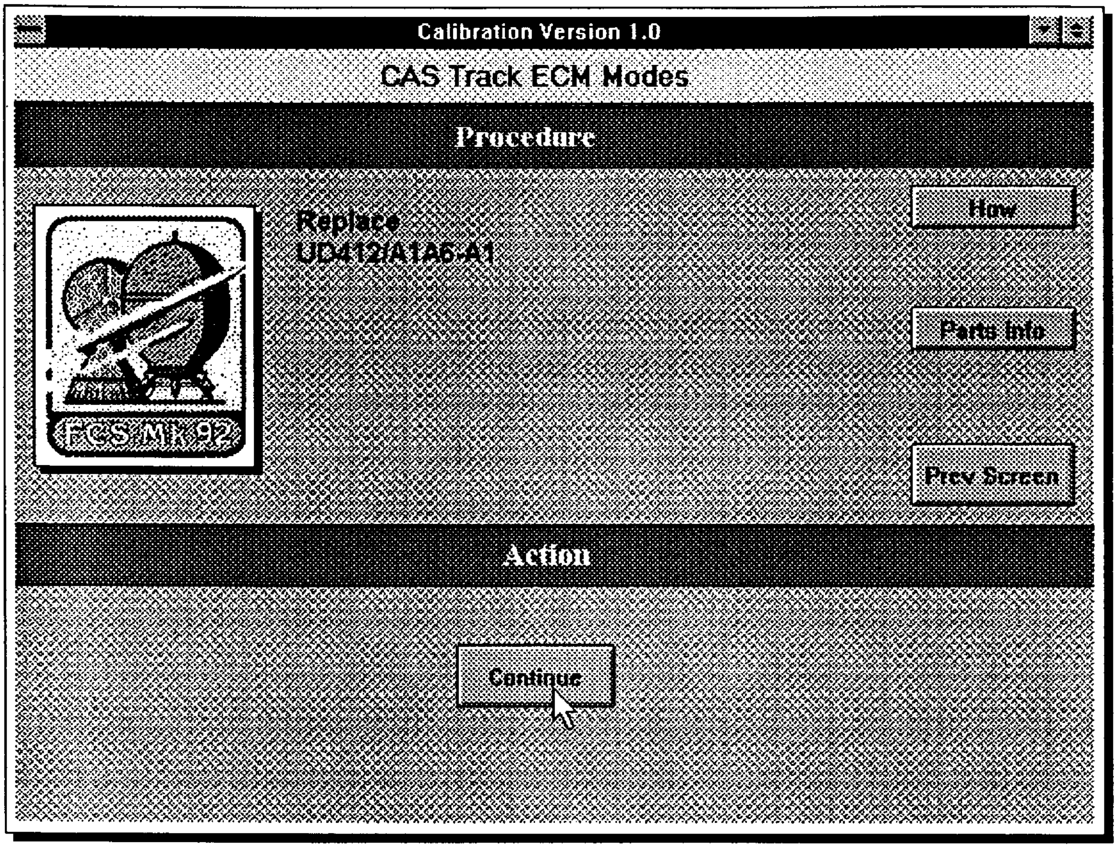

FIGURE A9. MK92 MAES Recommendation Screen.