SYSTEM INTEGRATION OF KNOWLEDGE-BASED MAINTENANCE AIDS

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ABSTRACT

There are many examples of knowledge-based fault diagnosis advisors for corrective maintenance of complex equipment. However, such advisors are only part of an overall maintenance solution. To be used effectively, diagnostic advisors must be integrated with other existing and forthcoming systems, such as Automated Test Equipment and maintenance databases. Successful fielding of knowledge-based systems requires consideration of integration issues throughout the design process.

I INTRODUCTION

There are many examples of knowledge-based fault diagnosis advisors for corrective maintenance of complex equipment. However, such advisors are only part of an overall maintenance solution. To be used effectively, diagnostic advisors must be integrated with other existing and forthcoming systems: maintenance history databases, spare parts inventory databases, Built-In Test (BIT) and Automated Test Equipment (ATE) systems, and other knowledge-based advisors for non-diagnostic maintenance tasks requiring expert knowledge. Therefore, successfully deploying a knowledge-based maintenance advisor requires more than capturing expert diagnostic reasoning. It also involves substantial effort in interfacing the advisor with other physical and information systems to deliver diagnostic advice appropriately within the constraints of the encompassing maintenance support framework.

This paper describes the Mark 45 Fault Diagnosis Advisor (Mark 45 FDA), a prototype knowledge-based advisor for the diagnosis and repair of the Mark 45 Naval Gunmount*. We will describe the system integration issues and how they are addressed by the Mark 45 FDA.The discussion will cover three topics addressed in the development of the system testbed:

- BIT/ATE integration - the integration of a knowledge-based diagnostic advisor with existing test equipment and the additional diagnostic knowledge it requires
- Interactive media - the use of interactive graphical and text media for delivery of procedural instructions to the user
- Procedure planning - the planning of context-dependent instructions for equipment tests and repairs during fault diagnosis.

We will also discuss other issues not specifically addressed by the current system testbed, but important to maintenance system integration.

II THE MARK 45 FAULT DIAGNOSIS ADVISOR

A. Testbed Overview

The Mark 45 FDA testbed hardware contains three major components, a special purpose symbolic computer, a videodisc player, and a desktop personal computer. The symbolic computer is the central computing facility in the group and controls all consultations. The videodisc is used to present supplementary material during consultions, under the control of the symbolic computer and FDA software. The videodisc player outputs an NTSC (standard TV broadcast quality) signal that is input to a low resolution color monitor. The personal computer emulates the abilities of the embedded Mark 45 microprocessor to access sensor data. The symbolic computer communicates with the peripheral components with RS-232 standard serial communications.

The Mark 45 FDA software system (Figure 1) contains the fault diagnosis advisor, a procedure planning system, and a text and video procedures database.

B. Fault Diagnosis Software Design and Applicability

The Mark 45 FDA was developed as an initial application testbed to construct and refine a generic expert systems software architecture applicable to a family of equipment fault diagnosis problems. The architecture provides inference and control structures that exploit structural and functional features of the equipment family. Our intent was to implement a software framework to facilitate the efficient development of fault diagnosis advisors for members of the family. A more detailed description of the Mark 45 FDA software architecture may be found in (Wescourt, Powell, Pickering & Whitehead, 1986).

The Mark 45 FDA framework is implemented using the S.1

* The Mark 45 is a 5-inch 54-caliber gun developed by the FMC Northern Ordnance Division for use on Navy destroyers, frigates, and escort ships.

expert systems programming language system.* It consists of a "package" or "library" of S.1 source code that includes definitions of object classes, associated attributes, and control blocks (i.e., procedures). The targeted electrical-hydraulic-mechanical (EHM) equipment family includes the Mark 45 and other weapons systems manufactured by FMC. More generally, we believe the software framework can be applied to other material handling/conveyance systems that share design and operating features with the Mark 45.

Members of this EHM equipment family are composed of subassemblies that perform functional subcycles. Each assembly may perform several subcycles. Conversely, a subcycle may involve more than one assembly. The relationships among assemblies and subcycles consist of electrical, hydraulic, and mechanical interlocks. A typical electrical interlock consists of a switch mounted to detect the position of a moving mechanical part within an assembly. When the part moves to a critical position, the signal from the switch is analyzed by electrical/electronic logic. The logic output may terminate or initiate the activation of another assembly. Such interlocks ensure the coordination of the subcycles performed by the assemblies.

The inference structure of the generic architecture decomposes EHM equipment fault diagnosis and repair into four main subproblems. The first determines a **fault.cycle** whose value is the equipment subcycle directly affected by the fault. The second determines **hypotheses** that are known problem causes for the **fault.cycle.** The third determines which of the **hypotheses** is the **cause.of.problem** based on inferences from attributes describing equipment-specific tests. The last determines **recommended.repair** for the **cause.of.problem**, taking into account the urgency of the situation, the user's skill or certification, and information about the availability of tools and parts. This problem solving model integrates abstract diagnosis concepts (*symptoms*, *hypotheses*, and *causes*) with equipment-generic concepts (*operating mode* and *fault cycle*). It contrasts with one that iteratively refines a hypothesis about fault location within the specific physical structure of the equipment.

The problem-solving model for EHM equipment fault diagnosis incorporates an extensive control structure tailored to the inference structure described above. Besides providing explicit control over the sequencing of the four main subproblems in the inference structure, the control structure effects detailed

* Developed and distributed commercially by Teknowledge, Inc. S.1 is a second-generation knowledge-based systems tool, a descendent of the EMYCIN and other early tools. The primary language features of S.1 are rules, procedural segments called control blocks, and data objects called class instances and attributes. S.1 represents factual knowledge using an extension of "object-attribute-value" triples. For example, for the object called "Gunmount", the attribute "Breech-Position" may have the value "Open". In S.1 judgemental knowledge is expressed in "traditional" condition-action rules. Given some input facts, a rule asserts new facts as true. Control blocks are the language structure which allows the expression of control knowledge outside the built-in inference-engine, a rule backchainer.

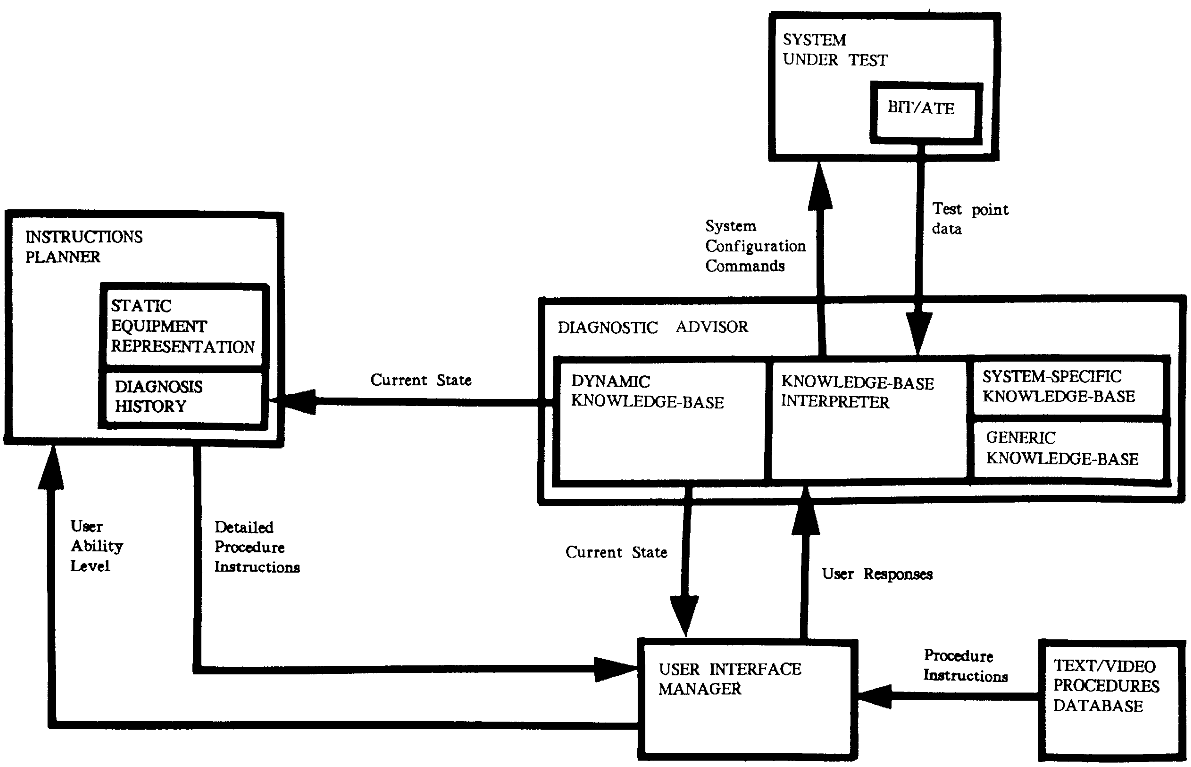

Figure 1. Architecture Diagram

control within the **fault.cycle** and **cause.of.problem** subproblems. It also provides a mechanism for handling problems with multiple concomitant failures by applying the inference structure iteratively for the **hypotheses**, **cause.of.problem**, and **recommended.repair** subproblems.

The diagnostic knowledge of the Mark 45 FDA is coded within the generic architecture. Currently the fault diagnosis knowledge provides substantial coverage of 4 of the 14 Mark 45 assemblies, exhibiting expert-level performance in those areas. This part of the system has over 500 rules and identifies over 300 faults.

C. BIT/ATE Integration

During fault diagnosis, experts use BIT/ATE data to assist fault isolation. BIT/ATE is a tool for these experts, providing partial solutions but not complete diagnoses. Therefore, BIT/ATE data access and reasoning are necessary, but not sufficient, for a knowledge-based system to achieve expert diagnostic performance.

Integrated use of BIT/ATE data increases the power, but also the complexity, of a knowledge-based advisor. The amount of raw data available from BIT/ATE is large and using it effectively requires recognizing which data are important. A knowledge-based advisor can capture the experts' use of BIT/ATE data and recognize key data combinations. The knowledge base may also be designed to recognize BIT/ATE inconsistencies, an ability limited to only a few expert troubleshooters. When the BIT/ATE data are inconsistent, the advisor can focus within the BIT/ATE system during fault diagnosis.

The Mark 45 testbed diagnosis system is integrated with simulated test equipment for the Mark 45 control system, giving the diagnosis system access to more than 100 status points monitored by the Mark 45. A simulator was used to generate representative test data allowing us to develop and fully demonstrate the FDA to BIT/ATE interface. The testbed knowledge base includes expert fault diagnosis and BIT/ATE consistency-checking knowledge.

For the Mark 45 and similar systems, the primary use of BIT/ATE data is isolating faults to equipment subcycle. The Mark 45 FDA rules for subcycle isolation represent the experts' ability to determine the state of the equipment from a small subset of the BIT/ATE data. In addition, the BIT/ATE data is used throughout the fault diagnosis, along with other test and observation data, in attempts to confirm specific possible fault hypotheses. Our experts' used system functional design documents to derive this knowledge by tracing details of the system subcycle.

The BIT/ATE data is also tested for consistency, based on expert knowledge of the physical device. Some combinations of BIT/ATE data represent physically impossible configurations of the equipment and indicate failures in the BIT/ATE system. Tests for these physically impossible sensor value pairs were compiled by Mark 45 design engineers and are included in the Mark 45 FDA knowledge base. More complex combinations were discussed with the experts or derived by analysis of Mark 45 functioning.

During a consultation, when rule premises are tested that require BIT/ATE data they trigger an I/O function that requests data point values from the test equipment. The test equipment responds by transmitting the data through a serial connection from the test equipment to the FDA host computer. The I/O interface is transparent to the rule processor. Thus, rule premises use BIT/ATE data as they would other test point data requested from and supplied by the user. The direct interface allows the FDA to obtain and use large amounts of such data without effort by the user.

The BIT/ATE reasoning portion of the prototype knowledge base contains over 300 rules and identifies nearly 100 faults. Calculations based on engineering data indicate that this portion of the knowledge base will eventually contain nearly 900 rules identifying over 650 faults.

D. Interactive Media Presentation

Traditional media for presenting maintenance information have inherent problems. Usually, maintenance manuals are large and complex, requiring strong reading and cognitive organizational skills. A single diagnosis problem may require information presented in various, unrelated, forms and spanning several volumes. Continual updating of these manuals tends to increase demands on organizational skills. Within the domain of military equipment maintenance, low basic skill levels intensify these problems. In addition, high personnel turnover precludes the use of extensive training as the primary solution to the maintenance performance problem.

Computer systems with multiple interactive media can overcome the deficiencies of traditional media. Program control of the access and presentation of diagnostic information significantly reduces the organizational skills required. Updates to the information may be integrally incorporated with existing information so no additional burden is placed on the user. Computer-based user interaction may require only limited training. Yet, delivering procedural instructions interactively to less experienced technicians enables them to complete more complex and sophisticated procedures with fewer diagnosis and repair errors (Halff, 1984).

The systems architecture of the Mark 45 FDA testbed incorporates several interactive media to support fault diagnosis and repair. The media include videodisc stills and sequences, digitized drawings, and a text description hierarchy. Access to the various media is integrated into a single menu-based "help" facility, available to the user upon request during a diagnostic consultation. Coordination between the diagnostic advisor and media controller is achieved by generating side-effects of advisor actions that associate requested information types, current consultation focus, video sequences, text, and digitized images. Thus, the diagnostic system automatically accesses and displays relevant information on request, eliminating manual information search.

The video material includes schematics, film sequences and stills illustrating diagnostic procedures, settings and results, and repair procedures. Videodisc frame numbers are indexed by diagnostic repair or test description, and information type. Upon request, software functions retrieve the appropriate videodisc frame numbers from the database and operate the videodisc player via a serial interface.

Digitized drawings from existing reference material support detailed instructions, allowing the technicians to use familiar material. When the user requests access to reference material, the advisor locates and presents the information. Drawings are accessed and displayed during disassembly and repair sequences to illustrate the parts associated with the ongoing procedure. The drawings are labelled so that associated text descriptions can refer to individual parts by name.

Text help for tests and observations is available at different degrees of detail suited to users with differing levels of experience. The text help is available in detail levels from "overview" to "step-by-step" and the level of viewing is user directed. Each troubleshooting test or observation, in all but the most detailed level, has associated text instructions stored in a database. The most detailed level of instructions cannot be represented simply as text in a database. Instead, it is generated by a procedure instructions planner.

E. Planning Requirements for Procedural Information

A fault diagnosis advisor can advise a user of *what* tests/observations to perform to diagnose the cause of a fault condition. We have found that, in their present form, advisors do not provide a fully satisfactory capability to advise the user *how* to perform recommended tests/observations or the recommended repair for a fault. The use of interactive media, described in the previous section, by itself is an incomplete approach. The problem is that FDA designs assume that a specific test/observation, represented by an attribute, is equivalent across contexts. However, we have observed that in the Mark 45 FDA, a given test/observation is sometimes used to diagnose different faults, sometimes in different operating cycle contexts. The detailed procedures for performing many tests/observations are context-dependent: they involve some actions—equipment configuration or disassembly—that may have already been performed (and perhaps later undone) for prior tests/observations. In general then, correct instructions for *how* to perform a test/observation can vary for the different fault cases where it is required. Therefore, lengthy procedure instructions for a recommended actions cannot simply be stored in an associated static definition. Anderson, et al (Anderson, Cramer, Lineberry, Lystad, & Stern, 1984), indicate that to address this problem, a successful intelligent advisor should be viewed as a cooperating ensemble of expert systems and interface mechanisms.

Our approach specifies procedure details as a hierarchical plan. In a dynamic environment, high-level plans may require significant modification during execution depending on situation context. Thus, the successful completion of high-level plans depends on dynamic planning of lower-level details. Our approach uses a dynamic planning subsystem which cooperates with the fault diagnosis advisor to provide procedure details.

We have implemented an interface for accessing supplementary instructions from the existing Mark 45 FDA. We have also developed a prototype subsystem for planning procedure instructions. The planner is a primarily goal-directed system that composes step-by-step procedures for maintenance tasks using a procedural network representation of the diagnosis history.

The planner maintains a "record" of the state of the Mark 45 throughout the diagnostic consultation based on its initial state and the effects of test procedures conducted during the consultation. This record is maintained using a static hierarchical representation of Mark 45 components and their

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REMOVE  THE PLUG.27.
IS THE PLUG.27 REMOVED  ?
(Y or N) No.

IT IS NECESSARY FOR THE PLUG.27 TO BE REMOVED BEFORE WE C
AN CONTINUE.

DO YOU KNOW HOW TO REMOVE THE PLUG.27?
(Y or N) No.

LOCATE IPB FIGURE 35, SHEET 1, DETAIL Y-Y IN VOL. 7.  USE
 A 1/4 INCH ALLEN TO UNSCREW THE PLUG 27.

REMOVE  THE PLUG.27.
IS THE PLUG.27 REMOVED  ?
(Y or N) Yes.

REMOVE  THE PACKING.28.
IS THE PACKING.28 REMOVED  ?
(Y or N) Yes.

REMOVE  THE CHECK.VALVE.SLEEVE.29.
IS THE CHECK.VALVE.SLEEVE.29 REMOVED  ?
(Y or N) █
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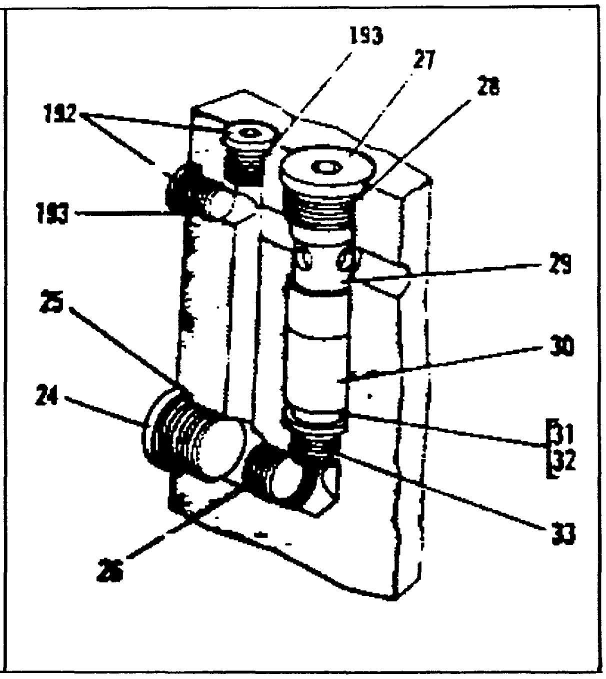

Figure 2. Mark 45 FDA Detailed Repairs Output Screen

possible actions. When a plan is required, the instruction generator builds the procedure using the representation of the device's current state and the structural knowledge of the Mark 45. The planned procedure is composed of the links between the current device state and the device state that satisfies the preconditions of the desired diagnostic test.

Figure 2 shows an example of detailed repairs being presented to the user. The repairs were planned by the prototype planning subsystem and are presented using text accompanied by a digitized drawing.

III FURTHER ISSUES

For the Mark 45 FDA and diagnostic advisors for similar systems, there are a number of design issues that require future system expansion to field the maintenance aiding system successfully. Issues include hardware and software delivery environments, and integration with a variety of maintenance logistics systems.

A. Delivery Media

Delivering a diagnostic advisor into the field requires solutions to two fundamental problems. First, the field environment may be hostile toward the hardware required by the advisor. This may be reflected in specific customer requirements, e.g., requiring MILSPEC hardware. Second, environmental restrictions may also require special user interface hardware. For example, space restrictions in the users' environment may require portable, remote user interfaces to access the advisor, or embedding the maintenance aiding system within existing operating and maintenance equipment.

For U.S. military customers acceptance of software products requires compliance with MIL-STD 2167, implementation in Ada. However, it is not clear that knowledge-based software can be implemented in Ada so that it is easily maintainable: Ada does not have rule structures. Currently U.S. military customers will accept knowledge-based software products in languages other than Ada. However, it is anticipated that some form of compliance with the standard will be required in the future. We expect that inference control programs will be viewed as applications and will be implemented in Ada. Knowledge-bases, however, will be viewed as data and will not be implemented in Ada. Thus, while we expect that advanced knowledge-based system tools will continue to be applicable, we expect that their implementation in Ada, and ability to interface to other Ada programs, is essential for military applications.

B. Integration with Logistics Management Information Systems

Currently, the diagnosis advisor collects data directly from the faulty system, and from the user. Yet, our domain experts indicate that in some cases they examine system history data to assist in forming their diagnostic hypotheses. Integration of the advisor with a maintenance history database could allow the automation of expert, history-based, diagnosis reasoning. For example, the frequency of particular faults occurring for a group of the devices could change the order in which hypothesed fault are tested. Similarly, integration with a current parts inventory database could allow the advisor to structure the investigation of faults based on the availability of spare parts. Finally, the diagnostic advisor could maintain records on maintenance actions automatically for use in higher level planning and logistics. For example, an integrated logistics system could anticipate spare-parts needs based on the maintenance history of a group of the devices.

The primary issues for integrating these additional systems are data access and interpretation. Each external data source must represent the data in a form which meets the needs of their primary users. In addition, the data must be represented so that it is accessible and interpretable by the fault diagnosis advisor. Thus, the knowledge-base representation chosen for the diagnostic system must allow access to external data and programs. Further, the representation of external data should be analogous to that of the internal data so reasoning methods are independent of data source.

IV CONCLUSIONS

One focus of our development of the Mark 45 FDA testbed has been the integration of multiple capabilities to produce a complete knowledge-based maintenance aiding system. We have successfully integrated multiple interactive presentation media, existing BIT equipment, and multiple knowledge-based subsystems in a prototype maintenance aid. We have also considered future issues involving integration of additional subsystems into a comprehensive maintenance aiding and logistics support system to help insure the extensibility of the system architecture. We believe that effective development, fielding, and support of knowledge-based systems requires consideration of these issues throughout the design process.

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