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The VLS Tech-Assist Expert System

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■ The vertical launch system (VLS) tech-assist expert system is being used by the in-service engineering agent as a force multiplier to maintain the readiness, with fewer resources, of a growing population of VLSs in the U.S. Navy fleet. This article describes the collaborative development of this knowledge-based system for diagnosis; its main features, including case-based and model-based reasoning; and the lessons we learned from the process.

The vertical launch system (VLS) is the U.S. Navy's premier missile launch system for surface ships. The VLS is modular, and its configuration is tailored to the individual ship. Depending on ship type or class, ship configurations have one or two launching systems. A ship can carry between 61 and 121 missiles. At the end of fiscal year 1993, about 73 systems were deployed on 46 ships; these numbers will almost double in the next 5 years.

The VLS Department of the Naval Surface Warfare Center–Port Hueneme Division is the in-service engineering agent (ISEA) for the VLS. Among its life-cycle support activities, the ISEA provides technical assistance to the fleet in resolving VLS problems through diagnosis and repair.

The VLS maintenance philosophy is built on general navy safety rules and the four VLS cardinal rules of safety, all intended to ensure the safety of personnel and ordnance and prevent the possibility of an inadvertent launch. Only certified naval personnel are allowed to troubleshoot the system using ISEA-approved procedures documented in on-board manuals.

When the on-board procedures are not sufficient to resolve the problem, a tech-assist message is sent to the ISEA. ISEA engineers are assigned to the case to develop additional fault isolation or repair procedures, which are then communicated to the ship to resolve or repair the ship's problem.

In the current defense budget environment, the staff level at the ISEA will not be allowed to grow and keep pace with the doubling of the VLS population in the fleet and the increased work load. In fact, for fiscal year 1994, the funding to support the VLS fleet is half of the projected amount. Coupled with the natural attrition of VLS experts, these factors place severe pressure on the ISEA to help maintain readiness in the VLS fleet. The ISEA has considered knowledge-based–system technology as a force multiplier to maintain VLS readiness in the fleet with proportionally less resources.

The Role of the VLS Expert System in the Tech-Assist Process

The VLS tech-assist expert system (VTAEXS) has been integrated into the tech-assist process. It makes the process more efficient by having the engineer spend more time doing engineering and less time researching and performing administrative duties and by providing the means by which the paperless workplace can be realized. It achieves this level of efficiency by automating the method of logging tech-assist records, enabling easy access to expert knowledge, providing an enormous amount of online documentation with an efficient interface to use this documentation, and generating response messages to the fleet.

The engineer no longer maintains paper records when working on a tech assist and no longer spends time generating paper reports. VTAEXS provides a template for users to log all specific tech-assist information and record all information used in solving the tech assist. This information is now in an electronic database; so, it is much easier to search past information for failure trends. This feature is important because, currently, more than 500 historical tech assists are on file.

Having convenient access to expert knowledge is important. In the past, we have seen users reinvent solutions because they did not have access to previous experience on the same fault. This lack of available information has led to wasted resources and, in some cases, has generated responses to the fleet that were not accurate enough. VTAEXS provides expert advice that is consistent and always available to the user. The system recommends solutions and explains the expert's rationale based on information that is specific to the current situation.

In addition, complete online documentation (text and graphics) is linked to these solutions, thereby providing information that is related to each specific situation. This online documentation is easily navigated and viewed. The information that is used by the ISEA is in many forms and is not centrally located. As more information is converted to electronic media by way of CALS (continuous acquisition and life-cycle support), VTAEXS provides the means to have information readily available and easy to maintain. Responses to the ship are in strict message format, and VTAEXS gives the user the capability to take corrective-action procedures from the knowledge base and generate responses in navy message format.

Program Status

VTAEXS has completed two development phases and has undergone a six-month operational evaluation. Its development was completed in approximately 24 months. It has been used by the ISEA staff engineers to assist in troubleshooting fleet VLS problems since 1 October 1993 (the beginning of fiscal year 1994). This application has developed into a driver for additional business-process improvements and a model for other knowledge base system applications.

Case-based reasoning has emerged as the centerpiece of VTAEXS. It was a natural fit given the ISEA's large accumulated tech-assist case experience. It has been relatively inexpensive to build and is easy to maintain. The maturity of the available commercial off-the-shelf tools has made this development a low-risk proposition. In contrast to case-based reasoning, the promise of model-based reasoning is as yet unfulfilled. Although a prototype VLS modeling capability has been included in VTAEXS, the reasoning is not yet automated (see The Role of MBR).

During the VTAEXS operational evaluation, incoming messages were processed in parallel: One engineer entered tech assists into VTAEXS, and another performed the routine analysis. A small team of domain experts compared and evaluated the results from the two processes after each intermediate step, prior to sending return messages. The better response was used in the ship-bound reply, and deficiencies in VTAEXS's handling of the case were documented. When the ISEA reached a level of confidence with the performance of the system, VTAEXS was put into operational use.

The current case base contains 74 distinct cases grouped into 10 classes. These cases include almost 500 questions and 200 actions. They were developed first because they were high-priority problems. As VTAEXS continues to be used, unresolved problems, along with their solutions, will be evaluated for inclusion in the case base.

The ISEA receives an average of 12 tech-assist requests each week. The initial experience has shown that an engineer assigned to a case can generate a response to the ship in less time using VTAEXS and that most junior engineers have a higher degree of confidence in their work and work more independently using VTAEXS than when using traditional methods. A goal in developing VTAEXS was to reduce the number of message cycles needed to resolve tech assists; it is too early to evaluate this objective yet.

A configuration-management process was established, and the necessary controls were in place before the program became operational. The configuration-control board meets quarterly (or as needed) to review VTAEXS performance and other life-cycle management issues. There have been no surprises in the tech-assist cases that VTAEXS has supported to date. Some fine tuning of the case base has occurred, and new cases continue to be added, as planned.

Return on Investment

As a navy organization, the ISEA is not in business to make a profit. However, there is tremendous pressure to reduce costs yet still satisfy customer (the VLS fleet) requirements for VLS readiness. To justify the cost of VTAEXS development, a financial model was built to consider the cost of performing the tech-assist process without VTAEXS and the expected costs using VTAEXS. The context was the planned growth of the VLS population in the fleet.

Figure 1 summarizes the costs and expected financial benefits at a gross level, apart from improved performance on an individual tech-assist case. The development began in fiscal year 1992, and the area between the solid and dotted lines approximates the cost for development. The peak in fiscal year 1994 represents the end of the operational evaluation and the beginning of production operation.

The model in the figure is not a budget. However, it illustrates the criticality of developing VTAEXS because current funding projections could not support the resource requirements implied by the model without VTAEXS.

To be conservative in justifying the development, the small productivity improvements shown in figure 1 are built into the model over time (the outyear improvements are compared to 1994, the base year, not the previous year):

Fiscal Year	‘95	‘96	‘97	‘98	‘99	‘00
Productivity Improvement (%)	10	15	20	25	25	25

We expect significantly better results but are reluctant to make unsubstantiated claims. Based on the actual costs to develop VTAEXS and conservative estimates of the benefits, the development will have paid for itself when the area between the curves to the right of the crossover point is equal to the area between the curves to the left. Based on our assumptions, this point will be achieved in the fiscal year 1998 time frame.

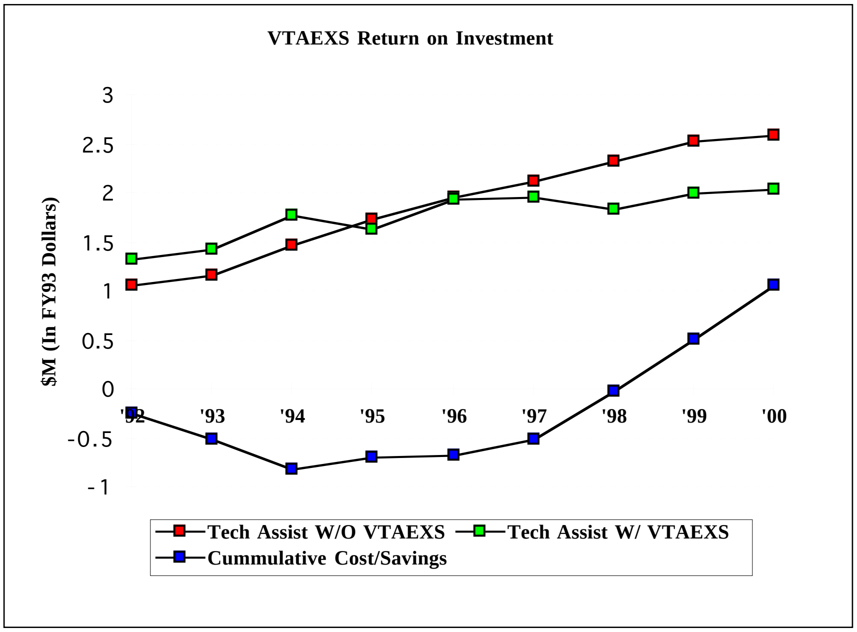

Figure 1. Cost-Benefit Analysis for VTAEXS Development.

Technical Approach

Vitro Corporation was tasked to perform an engineering feasibility study to assess the appropriateness of using a knowledge-based system to resolve VLS problems and the maturity of a knowledge-based–system technology for building such a force multiplier. The study documented requirements elicited from senior members of the engineering staff (domain experts) as well as junior members (intended knowledge base system users). The study led to an architecture and the identification of several commercial off-the-shelf (COTS) tools that were well suited to the task.

VTAEXS Architecture

VTAEXS principally uses case-based reasoning to match current cases with a library of historical and canonical cases. This facility is augmented by a model-based reasoning facility that supports user understanding of the technical issues implied by the case-based reasoning and analysis of problems not currently addressed by the case base. Both facilities are accessed through a graphic user interface. The COTS components and their associated responsibilities are given in table 1. Figure 2 shows a block diagram of the VTAEXS architecture. VTAEXS runs on an IBM 386/486 PC or equivalent.

A series of technical and organizational issues were identified as risk items requiring particular attention. These issues included (1) technology transfer and organizational acceptance of the resulting system, (2) partitioning of the problem space and representation of historical cases and the supporting knowledge acquisition, and (3) the potential role of model-based reasoning, and (4) the integration of online VLS technical documentation with the knowledge base system to create a powerful learning environment for the user.

As development progressed, these issues were resolved. The lessons learned from this process are described in this article. The organizational issues were evident from the first discussions about the system and had to be addressed satisfactorily before any development was undertaken (see Technology Transfer).

Representation of Historical Cases

One of the drivers for the case-based reasoning approach was that the ISEA had hard-copy

ART-IM (Inference)	Knowledge-based–system shell used in case-based reasoning
RAIMA DATA MANAGER (Raima)	Database management system used to store historical cases and tech-assist information
TOOLBOOK (Asymetrix)	User interface development language for Microsoft WINDOWS
CBR EXPRESS (Inference)	Case-based reasoning support software
DESIGN CENTER (MicroSim)	Simulation software for model-based reasoning
ACROBAT (Adobe)	Online multimedia documentation environment
C++ (Microsoft)	Dynamic link library environment
WINDOWS 3.1 (Microsoft)	Run-time environment
DOS 5.0 (Microsoft)	Run-time environment

Table 1. COTS Tools and Their Functional Allocation in VTAEXS.

records of more than 500 historical tech-assist cases over the life of the VLS. These cases would at least serve as a starting point for identifying the high-payoff problems in the VLS fleet. In the best case, these cases would require a little polish and serve as elements of the case base.

The historical cases were documented primarily as a matter of record of "corporate" memory. As a resource, they were not easily accessible and, therefore, were underused. To develop the case base that supports the case-based reasoning for solving current cases, we recognized that the historical cases, especially as they were documented, could be improved by adjusting the boundaries of intermediate decisions during the diagnostic process. The benefit of this reengineering is to make the case base more versatile and to more efficiently support the troubleshooting of logically adjacent problems, especially in terms of knowledge engineering. We are calling these *canonical cases* because, strictly speaking, their diagnostic process has been idealized through knowledge engineering, and they are not exactly the cases that are documented in the historical files.

This approach is analogous to the issues confronting the software reuse community, where software artifacts (for example, requirements, design, or code fragments) within a limited domain can be made reusable with an additional investment.

How large is the problem space? This question was debated several times during the development process and often arises in presentations. We decided that answering the question is unnecessary because there are potentially thousands of failure modes that have never been and might never be experienced in the fleet. We believe that significant value has been achieved through the development of a relatively small case base.

During the early stages of development, we adopted the notion of classes to group cases that were related to the same subsystem or function. This approach was used to show that the prototype could discriminate between similar manifestations of ambiguous problems rather than make a gross-level diagnosis.

If the case base ever reaches a size where run-time performance is a problem, it can be partitioned according to these classes to reduce the search space for pattern matching.

Structure of Cases and Pattern Matching

Historical cases reside in the configuration-controlled case base. The record structure of these cases is driven by the design of our COTS tools. Each case has the following fields: (1) title, (2) problem description, (3) associated questions with weights based on appropriate answers, and (4) repair actions to be taken. Within these fields are imbedded pointers to the hypertext document, where related information can be found regarding the theory of operation of VLS and how this case relates to the current tech assist.

Three text-matching algorithms are used in ART-IM: string, word, and character. VTAEXS uses character matching because of its robustness. The *:string algorithm* looks for identical (case-independent) text features to find a match. The *:word algorithm* finds a partial match if words match, regardless of their order. The *:character feature* uses *trigrams* (every three-let-

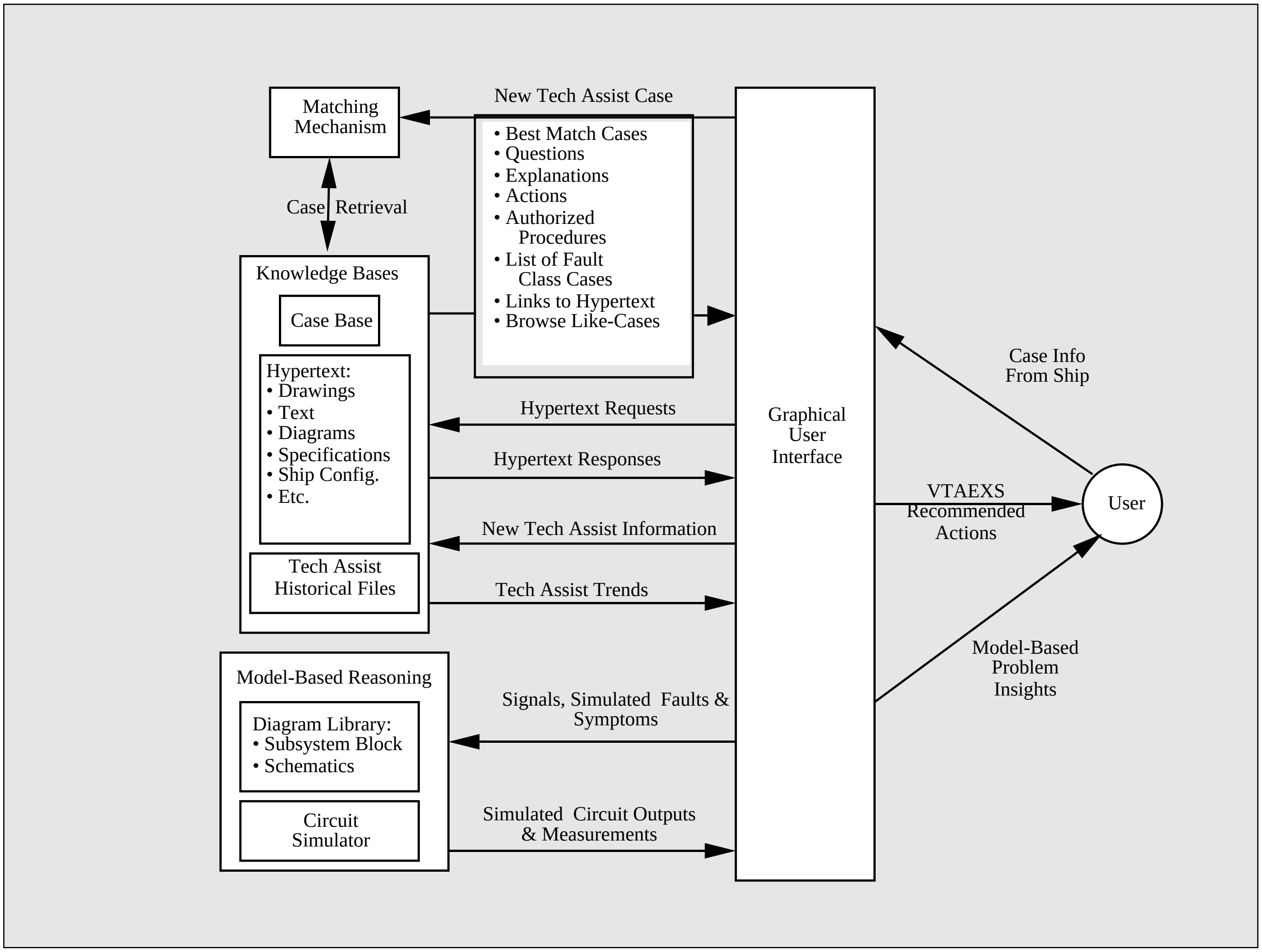

Figure 2. VTAEXS *Architecture.*

ter sequence in the text) to match text. This algorithm is the most robust of the three because it is resistant to minor misspellings; it is also the most computationally expensive. Despite the fact that the matching has no semantic basis, it is effective.

Example of VTAEXS Case-Based Reasoning

The following example from the VTAEXS case-based facility is intended to demonstrate how the expert system supports the user. The same hypothetical case is used throughout this section; all the data are fictitious but realistic.

Figure 3 shows the tracking screen that provides help-desk types of record keeping. Most fields contain pull-down menus with entries the user can select. For example, the User Name field (empty in the figure) contains a menu with the names of all the ISEA engineers who work on tech-assist cases. The Ships Problem field contains a free-form textual description extracted from the incoming message. This description can be imported as a file or typed by the user.

Once the case data have been entered, the user goes to the Search Case Base screen, shown in figure 4. Based on the user's entry of the problem description, VTAEXS uses ART-IM's text-matching algorithm to find candidates in the case base that have some degree of match. The best matches are listed at the bottom of the screen. The numbers next to each case indicate the strength of the match. These numbers are ordinal, not a probability of correctness; a strength-of-match score of 98 is not twice as good as a score of 49.

In the Questions About This Problem field, VTAEXS offers questions that, when answered, are used to adjust the strength of matches for each candidate solution. Not all questions

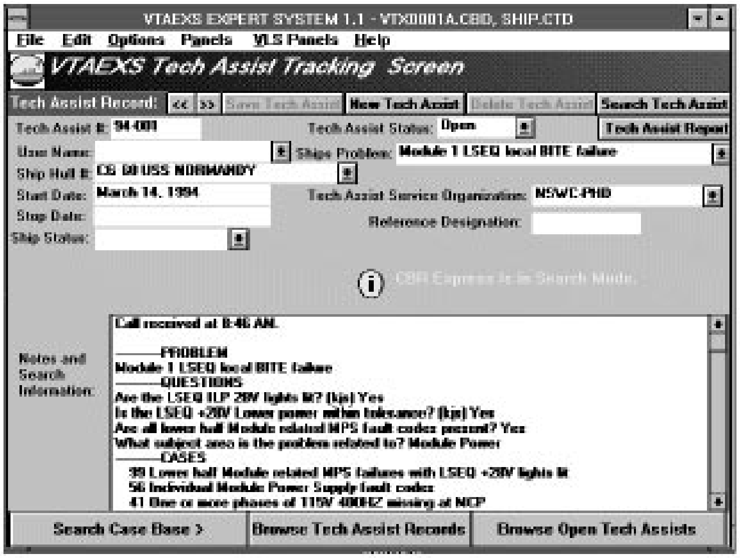

Figure 3. VTAEXS *Tech-Assist Tracking Screen.*

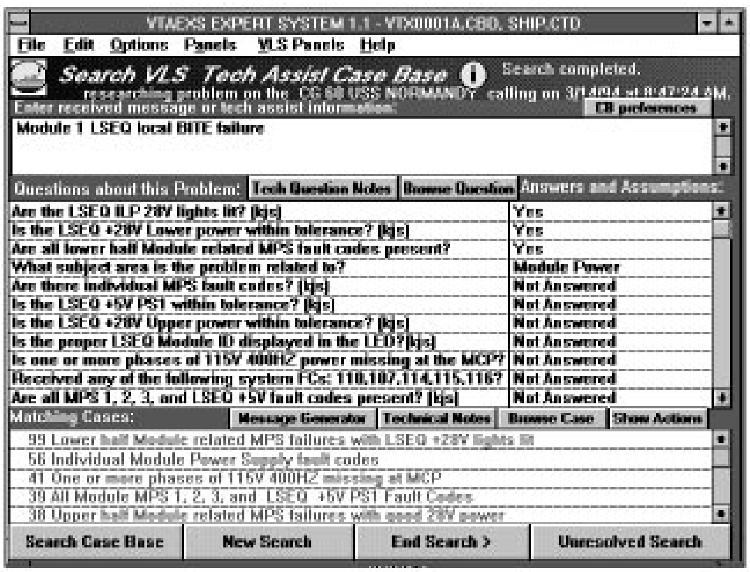

Figure 4. Search VLS *Tech-Assist Case Base.*

must be answered; the user might know some answers immediately or might need to find out others. A powerful feature of the system is the user interface, which includes alternate mechanisms to enter these answers. One such mechanism is to select Not Answered with the mouse and choose an answer from a menu. A second mechanism is to indicate equipment status in active graphic displays of each hardware panel on the VLS. The user can bring up these displays and select simulated buttons and indicators that are shown in color. This mechanism is a more natural way for many users to interact with the system. A screen image of part of the launch sequencer panel is shown in figure 5.

As the user answers questions, a matching case emerges, if one is in the case base. VTAEXS has matched a case entitled “Lower half module related MPS failures with LSEQ +28V lights lit” (MPS stands for module power supply). The recommended actions associated with this case are shown in figure 6; figure 7 shows the text of this matching case. Finally, VTAEXS includes documentation about why specific questions are important to the problem-solving process. This documentation is illustrated in figure 8.

When the user has found a case that matches the current tech assist, the engineer can export the recommended actions to a template editor and quickly generate an outgoing message. If the case base cannot find a suitable match, the user identifies the search as unresolved, and it is flagged for review by the configuration-control board.

Role of Model-Based Reasoning

During the feasibility study, model-based reasoning was identified as both a promising technology for VLS diagnosis and a more expensive method to implement than case-based reasoning. During the second development phase, a prototype demonstration was developed to show how modeling could be used to advantage in the tech-assist process. The focus of the demonstration is in the power-distribution subsystem.

Although the model-based reasoning is not tightly coupled to the case-based reasoning, it is accessible during case-based reasoning to help the user understand circuit behavior. In addition, if case-based reasoning does not find a matching case, the model-based reasoning facility can be useful in solving the problem, which has already occurred (see description later).

Unlike case-based reasoning, which models the diagnostic process, model-based reasoning models the system (in nominal operation and some failure modes) at some level of abstraction. The challenge was to find the right level of abstraction. Adding fidelity adds cost; reasoning from first principles at the discrete-component level was, therefore, out of the question.

Through discussions with the ISEA engineers, we were able to establish the right level of abstraction to support the current VTAEXS mission. The engineers felt that a structural model would be more valuable than a dynamic model in helping an engineer resolve a VLS tech assist. The system documentation is voluminous and difficult to navigate. By building an active structural model of the system, the user could descend the system-subsystem hierarchy to the point where a problem's manifestations can be observed and could easily trace the pathways that might cause or influence the manifestations.

Because the maintenance philosophy only allows replacement at the card level (lowest replaceable unit [LRU]), diagnosis of problems at the circuit or component level is not needed. Also, navy-wide and system-specific safety rules govern diagnostic procedures. Specifically, taking measurements of signals or voltages is not allowed when there is ordnance in the launcher. These rules constrain what a technician can do to isolate a fault; models of VLS circuits allow an engineer insights that might not be obtained from the actual hardware.

Example of Model-Based Reasoning

In a recent case, a problem was unresolved on the ship after several circuit card assemblies were replaced, as documented. The indications were a built-in test equipment (BITE) code and an illuminated lamp on the launch sequencer.

During the tech assist, several more cards were replaced, including one of two redundant power supplies. The problem persisted and was believed to be in the launch sequencer's backplane. Replacement of this component is among the most expensive and demanding repairs; it was replaced and still the problem persisted.

The model-based reasoning facility was being developed at the time and was used to assist the engineers in solving the problem. A hierarchical functional block model of the VLS was built. A representation of the applicable circuitry was developed in a circuit simulation environment.

Three simulated probes were placed in the schematic—at the voltage source of the launch sequencer and also at two output points (an indicator lamp on the panel and the BITE display). The simulated oscilloscope told a powerful story.

The first trace, the voltage input, should have only been +5VDC. In fact, there was an AC ripple from the second power supply (the one not replaced). The second trace, the BITE output, cycled between high and low. The nominal condition is that the BITE is high, which is why there was a BITE code indication initially. The third trace, the voltage supplied to the indicator lamp, was also oscillating; the lamp was flickering at a 30-millisecond

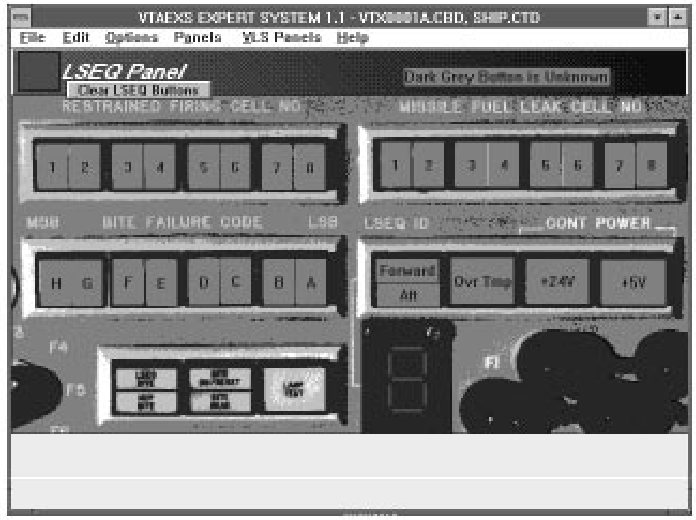

Figure 5. Launch Sequencer Panel Simulation for Data Entry.

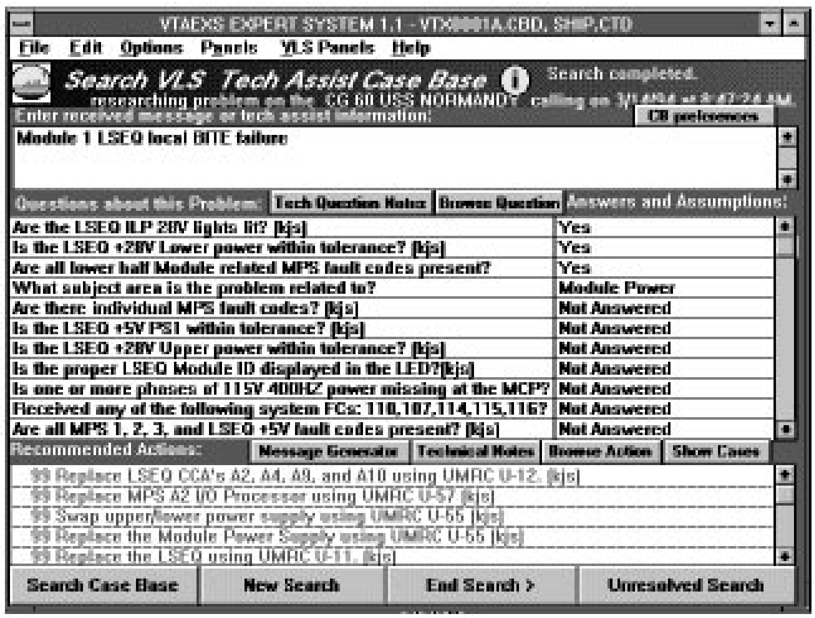

Figure 6. Recommended Actions in Matching Case.

cycle time, faster than the eye could discern.

All three indications pointed to the redundant power supply because the output oscillations were on the same cycle as the AC ripple. The redundant power supplies provide backup under certain failure conditions, but in this case, the redundancy masked the solution. The problem was solved by replacing the second power supply. Model-based reasoning has already proven its value in VTAEXS. We are currently evaluating how to automate this subsystem and integrate it with case-based reasoning.

As VTAEXS gained acceptance at the ISEA, the users identified new applications for the tech-

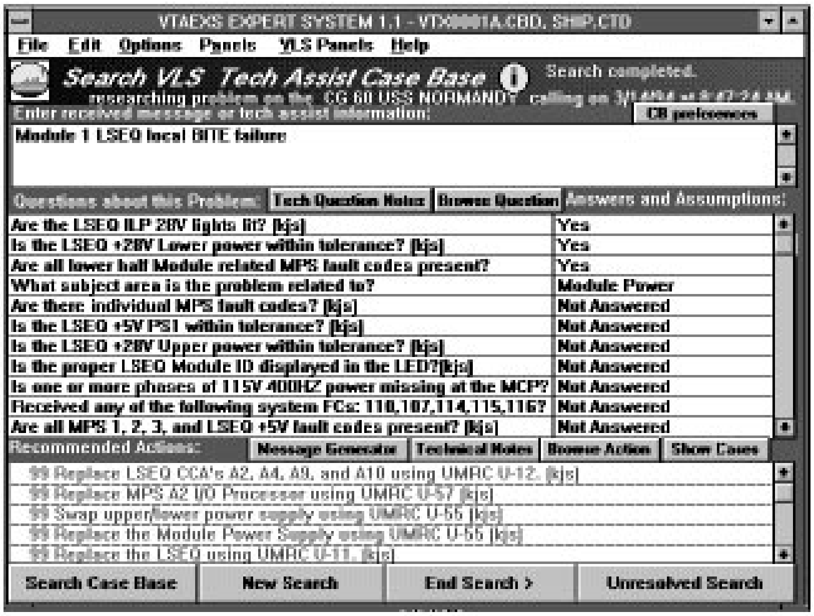

Figure 7. Text of Matching Case from Case Base.

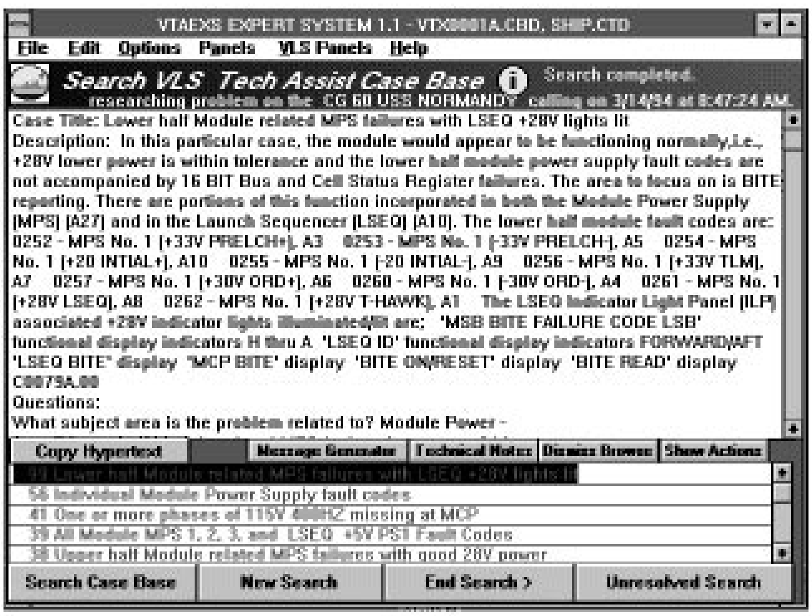

Figure 8. Explanation of Relationship between Questions and Current Case.

nology. A related but distinct role for the ISEA is in the engineering analysis of proposed changes to VLS and in the investigation of design deficiencies that might contribute to or cause high-cost problems. The constraints of these analyses are different than the LRU requirements for diagnosis and repair in the fleet. Analysis down to the component level can be indicated, and the engineers certainly are interested in the dynamic behavior of the system-subsystem components. This deeper level of model-based reasoning is being developed to support the engineering analysis mission of the ISEA.

Integration of Online Technical Documentation

From the beginning, there has been tension over the boundaries of VTAEXS; this tension concerns the degree of integration of existing documentation and the associated costs. Two factors were crucial in achieving the current result, where there is a significant and growing body of online resource material. The first factor was the importance of creating a powerful learning environment for the end user, as described in Organizational Acceptance. The second was the current generation of multimedia authoring tools that provide the ability to import vector and scanned documents, giving high-quality results with minimal author intervention.

The resulting VTAEXS implementation is entirely consistent with the Department of Defense initiatives in computer-aided logistics support and in interactive electronic technical manuals. Feedback from the users indicates that the online documentation has been a powerful tool because it makes diverse technical information accessible in a way that it has never been before.

Technology Transfer

The real challenge in this development project was to ensure that the investment was recouped and that the resulting system would, in fact, be an effective force multiplier. This challenge implied effective technology transfer, two important elements of which were evident during the development process. The first had to do with organizational acceptance of the expert system. The second was the requirement that the ISEA be able to provide organic maintenance at a manageable cost.

Organizational Acceptance

The organizational issues were cited as critical to the initiation of the project. The ISEA management had a series of concerns. The intended users of the system must, in fact, use it. The VTAEXS must be adapted to their business process, not the other way around. The users must not use the system as a crutch by substituting automated answers for their judgment and understanding of VLS and its failure modes. The ISEA should be able to provide organic, life-cycle support for VTAEXS at a low cost.

To address the initial concern, the feasibility study carefully documented the current business process and explained how VTAEXS would support the process. As in all expert system development projects, knowledge engineering depends on cooperative and committed domain experts. As the system has been used and user acceptance has developed, the system is viewed as nonthreatening. With this comfort level has come the recognition that the technology can be exploited further to achieve additional improvements in the business process. Small improvements are already being implemented. Significant improvements are being discussed (see Future Directions).

ISEA's future funding constraints make it clear that even though the number of VLSs in the fleet will double, the staff available to provide support will probably not grow and, in fact, will be cut back. VTAEXS was conceived as a force multiplier. Over time, as experienced engineers leave the organization, corporate technical memory will also diminish. The engineers' replacements will have less experience and will troubleshoot problems less efficiently until they gain the experience and expertise of the engineers they replaced. This process could take years. In this scenario, the ISEA was concerned about the knowledge base system becoming a crutch for the end user, whose accountability-responsibility for the answer sent to the fleet must remain undiminished.

To address this concern, the developers recognized that the users must have an active role during development to help the system reason about problem information and generate a recommended course of action. VTAEXS could not be a batch process where the input are entered, and the answer is returned. Rather, VTAEXS was developed as an interactive learning environment where model-based reasoning and online multimedia documentation allow the user to better understand the expert advice from the case base. There is a short course given to new users of VTAEXS, and the ISEA is considering incorporating the knowledge base system into other areas of responsibility, such as VLS training.

The initial concept demonstration prototype was developed by a small government-industry team. Vitro designed and integrated the architecture and performed knowledge engineering. Techmatics, the VLS support contractor, provided valuable technical data from various sources throughout the community. These data supported the knowledge acquisition and are included as supporting, online information. The ISEA provided the domain experts and end user representatives. The organization and responsibilities of the development team are shown in figure 9.

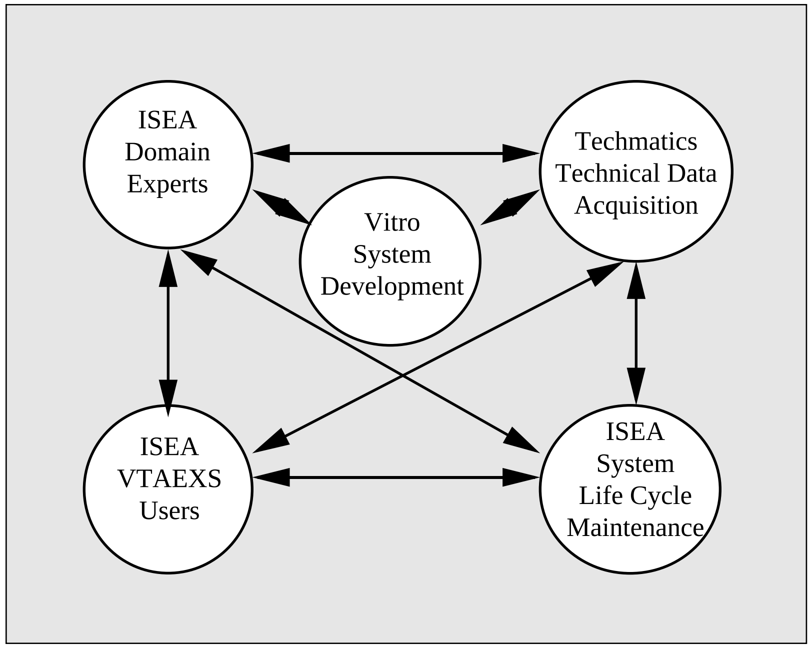

Figure 9. Organizational Roles and Responsibilities for VTAEXS Development.

This distributed team approach, although posing challenges, proved to be a master stroke. The roles and responsibilities of the development team have been the key to the successful transfer of the technology. The interfaces between these people have been the mechanism to get "buy in" (acceptance) from the community.

The group has generated new ideas and a series of refinements to VTAEXS as well as a sense of ownership. As each development phase has progressed, and the project has grown, the number of participants has grown, which has helped to overcome the barriers to acceptance.

ISEA staff members have come to accept the technology as useful and nonthreatening. The skeptics have become supporters as the technology has been demystified. Additional functions have been prototyped by members of the ISEA staff. The automated generation of the return message to the ship was initially seen as a nice-to-have feature but not intrinsic to the feasibility demonstration. Because it was an important feature to some of the users, they built it. This willingness to invest personal energy in improving the system is the best guarantee of its long-term success.

Organic Maintenance

Although ISEA staff members recognized the value in hiring outside experts to develop the knowledge base system, they did not want to become dependent on external organizations for its long-term care and feeding. If organic life-cycle maintenance had not been practical or cost effective, the system probably would not have been built.

This requirement for a maintainable system, although important, was easy to satisfy. First, the ISEA is also responsible for operational and other support software for the VLS; it had established configuration-management plans and procedures in place. Second, the maximum use of COTS tools minimized the maintenance burden of VTAEXS. Throughout the development process, life-cycle issues were planned for, and a growing number of ISEA personnel became involved to establish their roles. The Configuration-Management Plan that served the development process was correlated with the ISEA standard configuration-management approach, which facilitated the changeover at each delivery.

Future Directions

Current plans are to identify the cost-benefit of VTAEXS by measuring the performance of the tech-assist process with VTAEXS against the process without VTAEXS. Benefits will be measured by indicators such as time savings, accuracy, consistency, customer satisfaction, and ISEA user satisfaction.

Although there were organizational and technical constraints at the outset of the development project, the ISEA recognized that there was a set of possibilities that the knowledge base system might enable in the future. VTAEXS has matured, and these possibilities are now being discussed in a positive way. The transfer of knowledge-based system technology into the ISEA's daily business process is being leveraged informally for business-process improvement. The ISEA's concern for constraining the technology has given way to exploration of additional applications.

VTAEXS will continue to evolve as new problems are encountered in the VLS fleet. A configuration-control process has been created to manage changes to the knowledge-based system and its supporting knowledge bases. A problem-reporting mechanism identifies new cases for resolution and incorporation into the case base and instances where the historical solution does not apply, indicating a failure of the system to properly discriminate important differences between a current case and previously solved problems. As the case base grows under configuration management, the body of supporting online technical information will also grow.

ISEA staff members run an established training program for the sailors who maintain the VLS in the fleet, engineers in industry associated with the VLS design and manufacture, and members of the ISEA technical staff. The ISEA is currently considering how to leverage the investment in VTAEXS into the training curriculum to augment the primary course work and provide refresher training after course completion.

The original goal of supporting ISEA resolution of VLS problems has been realized. With the success of this effort, the idea of a shipboard version of VTAEXS is now being discussed.

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