Knowledge Based Systems Technology Applied to Naval Battle Management Decision Aiding*

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Abstract

The Force Requirements Expert System (FRESH) is a force employment and resource allocation decision aiding tool which supports the Commander in Chief of the US Pacific Fleet (CINCPACFLT). FRESH is an embedded knowledge based system, integrated with conventional components of the Naval Command and Control System in the CINCPACFLT Command Center. FRESH's development included innovations in knowledge engineering, system engineering, and man-machine interfaces. FRESH has resulted in demonstrated improvements to both accuracy and timeliness of decision making. FRESH has been deployed for two years. Development began in 1985; its cost was about $10M. The key to the successful introduction of knowledge based systems technology into the operational Navy environment has been the establishment and use of a testbed development and evaluation facility in the operational environment itself.

Introduction

The Commander in Chief of the Pacific Fleet (CINCPACFLT) has responsibility for U.S. Naval interests in the Pacific and Indian Ocean regions. He has nearly three hundred ships and over two thousand aircraft at his disposal as well as an operating budget of over four billion dollars per year. In the management of these resources he is assisted by a full time staff of experienced Naval personnel who constantly monitor situations, assess capabilities, develop plans, project outcomes, and evaluate strategies. Before assigning resources to missions, they collect, integrate and evaluate a large body of information, from both subordinate units and outside sources, and then develop and assess alternative courses of action. Due to time limitations, they normally work toward and arrive at satisfactory, but not optimal, solutions.

As part of the Battle Management component of DARPA's Strategic Computing Initiative, a functional architecture was developed for the application of Knowledge Based Systems (KBS's) technology to aid and improve this process. (This architecture is described in reference (1)). An on-site testbed in the CINCPACFLT Command Center was constructed and Artificial Intelligence (AI) technology was introduced. Component AI technologies were innovatively engineered into an effective KBS: FRESH - the Force Requirements Expert System. FRESH was integrated with existing operational

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support systems. It has resulted in more efficient and effective decisions. Its demonstrated utility has led to efforts to transfer its capabilities to other Navy command centers. The innovative approach used to develop FRESH has contributed to improvements in Navy acquisition policies and procedures for information systems. Other components of the functional architecture are in various stages of development and planning. Challenges remain to add additional decision aid capabilities and transfer them to other command centers with similar but distinct requirements.

Definition of the Problem

CINCPACFLT responsibilities are vast, both geographically and with respect to missions and resources. Mission requirements vary from simple to complex. Some are mutually exclusive and some are done in conjunction with one another. Some are well defined and others less so. Some are planned years in advance and some emerge without warning. Resources to match these requirements are units (ships, aircraft, and personnel) and Forces (collections of units). Allocation of these resources is a complex problem that is not amenable to linear programming type solutions. Units of the same type can differ greatly in their designed and actual warfighting capabilities. Considering the diversity of the nearly 300 ships (aircraft carriers, submarines, destroyers, tankers, minesweepers, etc.) and over 2,000 aircraft (fighters, bombers, patrol, land/sea based) as well as the 95 million square miles of ocean under CINCPACFLT's responsibility emphasizes the magnitude of the problem.

This resource allocation process consists of constructing forces from units, assigning forces to missions, and scheduling these missions. Decisions may be the result of deliberate planning or crisis response. Employment decisions are based on extensive knowledge about units and missions.

The complexity of the problem and time constraints normally limit a manual search of potential solutions to only the most obvious solutions, and, even then, decisions only consider the (ever changing) most important factors relating to allocation of a resource. This time constraint becomes more severe in crisis situations. This decision problem is made even more difficult by the continual reassignment of experts. This entire process is also performed continually in a "what-if" mode for contingency analysis and planning. Note that in "what-if" contexts, reasoning over notional forces is required as distinct from the reasoning about actual forces in the current operations mode.

Brief Description of the Deployed Application

FRESH is a force employment and resource allocation decision aiding tool. It operates in both a data-driven mode and a goal-driven mode. It automatically responds to readiness updates and supports force nominations and analyses of hypothetical new missions and schedule changes. As a resource manager, it monitors the readiness of fleet units and determines the impact of changes on current and planned assignments. In an analytic role, it generates and evaluates alternative courses of action, including the impacts of potential force redirection. It also acts as an interface aid to less experienced users, providing easier access to real-time operational data regarding readiness, position and technical characteristics.

In the generation and evaluation of alternatives FRESH performs a trade off analysis, weighing knowledge about warfighting capabilities, mission priority, readiness, planned schedules, operational utilization, personnel endurance, transit times and fuel cost. The system allows the user to modify these constraints to adapt to changing priorities. It provides explanations consisting of positive and negative impacts of alternatives, including impacts on future schedules of affected units, other ongoing missions, and contingency plans. FRESH also allows for the nomination of forces to fulfill specified force requirements.

The search space comprehended by FRESH is greater than 10 million elements. It considers:

165	platform/unit types
> 500	scheduled units
27	employment categories
> 400	employment terms
15	mission areas
> 100	mission critical equipments
29	Force level requirements
> 200	command elements
2540	Pacific ports of call
120	schedule days/quarter/unit
365	historical scheduled days/unit
1825	employment days per unit
> 10^6	ship and unit schedule days

95×10^6 square miles of ocean.

FRESH is an embedded KBS. It is dependent on and integrated in a distributed environment with conventional components of the Naval Command and Control System at the CINCPACFLT Command Center. Operational data is provided from the Operations Support Group Prototype (OSGP), a data base management, geographic analysis, and display system hosted on a VAX 11/780. The OSGP is the gateway for the receipt and storage of both dynamic data (e.g. Naval Status of Forces data, positional and readiness) and static data (e.g., ship characteristics, port characteristics). This data is automatically replicated on a VAX-11/785 computer system, which acts as a data server for FRESH. The data is organized as an ORACLE relational data base. FRESH's KBS software is resident on Symbolics workstations which provide environments for both users and developers. Workstations in the command center itself are tied to large screen displays for group decision support.

The user interface on the Symbolics integrates access to OSGP data base, analysis, and display functions, as well as to FRESH. A menu-based Natural Language interface based on Texas Instrument's (TI's) NLMenu is the primary man-machine interface. It provides 19 interactive screen formats and 13 classes of queries.

The expert system shell is KnowledgeCraft. (It was selected in early 1985 due to its context facility, required for "what-if" reasoning.) PROLOG is used in the alternative generation functions. Much of FRESH is coded directly in LISP.

Innovations and Technological Breakthroughs

FRESH's innovation lies in the application and combination of diverse AI technologies. The feasibility of effective interactions between KBS, existing data bases and command and control systems has been demonstrated. Technological innovations in knowledge engineering, system engineering, and man-machine interface were achieved.

Knowledge Engineering

Knowledge engineering for FRESH was a formidable job. Knowledge from several domains is required for Fleet resource allocation. This knowledge resides in multiple documents and human experts. The manual process which FRESH automates is itself distributed among many people, who are both the experts and users of the system. Knowledge engineering for FRESH required the integration of knowledge from multiple sources as well as the resolution of conflicts where the multiple sources overlapped or disagreed. Knowledge used for resource allocation required data interpretation by the experts from multiple perspectives prior to incorporation into the system. The prominent breakthrough in knowledge engineering was the use of diverse knowledge representations to handle the different types of knowledge and the creation of the ability to reason across these different data and information types to produce aggregate answers. As the knowledge bases evolved, continued verification was required to maintain consistency and to account for the integration of knowledge from multiple sources.

Knowledge and structure had to be incorporated into the system to allow it to deal with the fact that it was a continuously operating (vice transaction oriented) KBS. This included a mailbox feature for user defined alerts and continual updating of the current situation knowledge from the data base as real world events occurred.

To gain control of the knowledge engineering problem, a methodology of documenting and recording the knowledge in the system (including explanations and sources) was created and instituted. Implementation of this formalism was paramount in achieving success in the effort. It involved the creation of a knowledge description document to capture and record the knowledge base and a knowledge control board to resolve conflicts. The knowledge description document included the set of facts, constraints, rules, and relationships among them, that are required for the FRESH KBS to reason. The document is a handbook for the validation and verification of the FRESH knowledge base, accessible to both experts and knowledge engineers. This handbook:

- Guide experts who have contributed to shaping the knowledge base in examining its contents.
- Enable communication between the knowledege engineers and the experts regarding the knowledge base structure and contents to facilitate feedback on its accuracy and completeness.
- Provide a set of terms useful in discussing knowledge concepts.

The knowledge description document was updated approximately every 6 months. It also facilitated the turnover of knowledge engineers on the project.

In addition, a knowledge review board, consisting of experts and knowledge engineers, and chaired by a senior Naval officer, was established. This board had the authority to resolve conflicts between experts.

System Engineering

System engineering of an embedded KBS presented additional challenges which were magnified by the on site development process. System developers and users/experts worked together in the environment in which the system was being developed and used. Evolutionary development and rapid prototyping were combined with traditional system engineering to develop the integrated system. A large share of the initial effort consisted of the design and construction of the distributed hardware and software environment which support the KBS components. Key areas are discussed in more detail below.

Evolutionary Development. System development was proceeded by a requirements analysis. Knowledge and procedural based views of current CINCPACFLT command and control procedures were prepared. Based on these views a functional architecture consisting of five applications of KBS technology was developed. These notional applications were matched to the available and anticipated technology and to the underlying support systems. FRESH is the first of the five applications. The results of this process were recorded in a functional description which served as the basis for FRESH development.

The initial effort consisted primarily of the design of the environment, including the interfaces to the support software. Traditional software engineering methodologies were utilized, including design reviews and documentation. A functional design document was prepared to baseline the design. This document contained the overall system architecture, including hardware, software modules, required data, interface diagrams, and the man-machine interface design, as well as the initial design of the KBS components of FRESH. The document has been reissued periodically to keep pace with the evolution of FRESH. Rapid prototyping, including throwaway demonstrations in conjunction with the design reviews, was used for the KBS components.

Configuration Management. A configuration control board (CCB) was established to monitor the evolutionary development process. Working groups, reporting to the CCB, addressed specific areas. The knowledge control board is one working group; others include hardware, data bases, and software. System change requests (SCR's) were written by users and developers and prioritized by the CCB according to status (error correction, missing required functionality, new functionality), need, and an estimate of required implementation resources. Emergency SCR's could be approved on site for immediate fixes to the current version of the operational system. Software releases occurred approximately quarterly.

Several versions of the system were maintained. An operational version was under user control. A developmental version was used by the knowledge engineers. A tested baseline was maintained for backup purposes. Several demonstration versions, including complete data bases and scenario drivers, were frequently used as well.

Dynamic Data Bases. The original design required the KBS to issue calls to the data base as necessary during analyses. This proved unworkable due to the large number of queries needed to support even a single analysis, communication bottlenecks, contention between processes originating on different workstations, and performance limitations of the data base itself. The current design has the data replicated on the workstations at system boot time and included in the knowledge base. Dynamic updates are provided to all workstations as they occur at a typical rate of several thousand per day. Readiness monitoring, which uses these same updates as triggers, is typically turned off on all but one workstation.

Testing. Testing of FRESH was difficult due to the dynamic data bases. A valid test of the KBS required complete knowledge of the state of the Pacific Fleet. Further, in order to evaluate the results of a test, a situation similar to one that actually occurred was required. Testing was performed by saving a set of data base snapshots and scenario drivers representing situations similar to those encountered in Fleet operations. These scenarios were also used to support demonstrations.

Man-Machine Interface

The FRESH man-machine interface was crucial to achieving user acceptance. It provides extensive explanations and it presents an integrated pseudo natural language front end to both FRESH and the underlying support systems and data bases. The man-machine interface is based on TI's NLMenu.

The man-machine interface was designed to be a natural extension of the already existing OSGP interface; this allowed FRESH's capabilities to be presented as enhancements to an existing system instead of as an entirely new tool requiring additional training. It avoided conceptual distinctions between FRESH functions and existing data base, analysis and display functions. It also allowed a more effective and timely exposure of the information contained in the underlying data bases because the user did not have to possess an expert understanding of either the multiple data bases contents and structure or the OSGP command language to extract pertinent information. This encouraged users to try the FRESH functionality as well. The menu based natural language interface was natural to use, and it avoided the potential problem and accompanying user frustration from asking questions the system could not answer. A natural language integration document defined a FRESH KBS command language for interfaces to natural language front end, analogous to a data base interface language (e.g., SQL).

Explanations, consisting of the positive and negative impacts of alternatives, not only developed user confidence in FRESH but provided additional utility. In a staff decision making environment, users carry forward multiple alternatives, along with their positive and negative aspects, to allow for selection by a decision maker. As FRESH was developing, it was able to provide useful analyses even in situations when its absolute evaluations were not yet accepted.

Criteria for a Successfully Deployed Application

Criteria for a successful deployment of FRESH include improved decisions, significant operational use, and a Navy program to install it in other command centers. Statistical measures of value added were also generated from comparisons of proficiency (speed and accuracy) between working with and without the system to perform normal tasks.

Initially FRESH's results were used for comparison with the staff's recommendations; now FRESH's results are part of the actual decision making. FRESH has been used to support operations for about two years, both for routine readiness monitoring and for user initiated problem solving. The user base has grown to include not only personnel responsible for resource allocation but also personnel with other responsibilities who take advantage of the man-machine interface and the underlying data bases. Use has expanded from readiness monitoring and alternative generations to include regular production of eight reports and employment schedules. FRESH is particularly useful in time critical situations as it systematically considers all possibilities and guarantees that no potential solution or impact is overlooked. FRESH has matured into common acceptance and a user desire for expanded employment of the KBS technology.

The Vice Chief of Naval Operations directed in 1987 that the next generation operations support system for all Navy Fleet Command Centers include FRESH functionality and technology.

Payoff

FRESH is in daily use at CINCPACFLT and accepted into normal operations. The time associated with tasks and decisions has been greatly reduced. As of August 1988 improvements in both timeliness and accuracy of decision making have been demonstrated and documented:

- Readiness alerts can be performed in only a few minutes with FRESH, vice several hours without it; accuracy increased from 95% to over 99%.
- Alternatives can now be analyzed and ranked in a few minutes with over 85% accuracy as opposed to several hours and less than 60% accuracy before. Further, the number of alternatives considered increases from 12 to 100 in a typical case.
- Reports that previously required hours can be produced in 30 seconds with accuracy improved from 90% to 99%. Schedules can be generated in less than 2 hours with 99% accuracy compared to 8 hours and 90% accuracy without FRESH.

Translation of these improvements directly to dollar savings is inexact at best. More important than cost savings, however, is the ability to comprehend and make explicit tradeoffs between alternatives, resulting in more effective and efficient use of forces. It has been estimated that every 5% increase in efficiency results in an improvement equal to $150 million of additional resources, without requiring additional ships, airplanes or people.

System Deployment and Development

FRESH development began off-site 1985. It had been preceded by about one year of architectural development and knowledge engineering by Navy operational and technical personnel. Initial on-site installation of testbed resources and then KBS software occurred in stages during the first half of 1986. A demonstration with a snapshot data base took place in August 1986. FRESH began operating with live data in October 1986. Operational utility was initially validated in February 1987. Continued improvements in availability (50% in August 86, >90% in August 1987), processing speed, number of alternatives considered, frequency of readiness updates, and number of units have been achieved continuously. FRESH has been used on a regular basis by CINCPACFLT staff since August of 1987. The development effort gradually shifted from the development site to the operational site. Maintenance and enhancement is now performed on site.

FRESH was developed by Texas Instruments, Inc. and BTG, Inc. Personnel from Navy laboratories and other organizations also made significant contributions.

Direct development cost from 1985 through 1988 was ten million dollars. These costs do not include the indirect costs of Navy experts' time nor the costs to develop the underlying data bases and support software.

Conclusions

The key to the successful introduction of KBS technology into the operational Navy environment has been the establishment and use of a testbed development and evaluation facility in the operational environment itself. This approach allowed for the use of real-time operational data and enabled close coupling between developers and users. The technical management approach for the development of the FCCBMP applications blended traditional system engineering methodologies with the rapid prototyping techniques that have proven successful in the development of KBS. In retrospect, it is not surprising that a proper blend of these two development methodologies has turned out to be successful, since the actual system that has been developed consists of KBS modules integrated into a larger "intelligent system" consisting of both conventional and KBS components.

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