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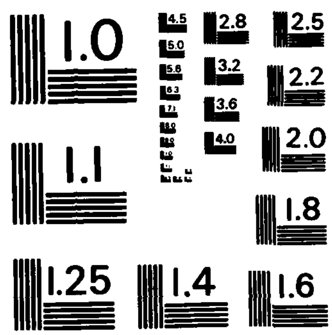

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Final Technical Report
August 1982

KBS: AN EXPERT PLANNING SYSTEM FOR CRISIS RESPONSE

The MITRE Corporation

J. W. Benoit, A. V. Lemmon and J. M. Selander

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This final report of the Crisis Management using Rule-Based Systems project describes the goals of the project, the Artificial Intelligence Technology on which it was based, and the results of the project. Knowledge Based Systems use knowledge obtained from planning experts in the Military Services to construct an automated system for planning an Air Show of Force. While the system is automatic, it is also highly interactive and allows close user control. A critique of the existing system and recommendations for future work are included.

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ABSTRACT

This final report of the Crisis Management using Rule-Based Systems project describes the goals of the project, the Artificial Intelligence Technology on which it was based, and the results of the project. Knowledge Based Systems use knowledge obtained from planning experts in the Military Services to construct an automated system for planning an Air Show of Force. While the system is automatic, it is also highly interactive and allows close user control. A critique of the existing system and recommendations for future work are included.

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EXECUTIVE SUMMARY

Crisis situations within the military establishment frequently require prompt and secure planning of complex actions. These plans are subject to error because the time sensitive nature of the activity prevents consideration of all of the viable alternatives and precludes thorough investigation of the selected alternatives. Further, security considerations may prohibit crisis planners from having access to the specialized experts and data required to complete the plan. In addition, this planning activity is often carried out by staff officers with limited experience. These problems inherent in present crisis planning methods have the potential to produce plans inadequately adapted to the military situation and the locale of the crisis.

In an attempt to mitigate the effect of these difficulties, the authors have investigated the best use of automated decision aids to assist the planner. This document is a final report on this effort. Not only would these decision aids have access to a large number of facts relevant to the plans to be developed, but, more importantly, these decision aids would also contain, in part, the accumulated knowledge and expertise of the best military strategists. Using Knowledge Based Systems, a technique from the field of Artificial Intelligence (AI), MITRE has implemented a demonstration system (KBS) in which the planning procedures, rules of engagement and deployment, mission requirements, and "rules of thumb" are embedded in the knowledge base. Most of this knowledge was obtained from experienced military strategists through interviews and direct observation of their method.

Background

A Knowledge Based System, also called an Expert System, is able to provide the assistance required to overcome many of the problems outlined above. Computer automation provides rapid access to a large body of facts for prompt and thorough crisis response planning. Of special note is the ability of KBS to use heuristic, ad hoc procedures and information obtained from experienced military strategists. Through these mechanisms, the system becomes a powerful, intelligent aid to the planner. Based on the rules obtained from the human expert, the system can make inferences through the successive application of several rules to solve problems (e.g., resolve plan deficiencies) through relatively standard procedures. On the other hand, Expert Systems do not perform well outside their domain of expertise. Also the current state of the art does not adequately support systems that attempt to learn or apply general principles to new situations. Thus, an Expert Crisis Planning System will perform well only in situations for which knowledge has been obtained and relevant facts are available.

System Goals

The primary goal for KBS was to provide a demonstration interactive system which would assist the staff officer in preparing a set of alternative plans in response to a crisis situation. Although KBS was seen as a potential Service-wide decision aid, it was recognized that the limited resources available for the development would severely restrict the scope of the effort. For these reasons, the crisis actions to be considered were limited to one scenario, an Air Show of Force, only extracts of the available data were used, and development of a sophisticated graphics user interface was deferred. The major goals, summarized below, were to:

- Develop crisis action plan alternatives
- Develop partial (incomplete) plans
- Correct plan deficiencies
- Check existing crisis action plans
- Give prompt but not "under fire" response
- Provide an interactive user-controlled system
- Explain plan choices as requried
- Allow for user supplied additional constraints (e.g., political)
- Allow for user override of any decision
- Develop restricted scenarios from a restricted database.

These goals have been attained and a demonstration system is available. The heuristic rules and deficiency correction techniques were obtained from military strategists and reflect procedures that would be followed in actual situations.

Evaluation

KBS has demonstrated that the techniques of Artificial Intelligence show substantial promise for the solution of military planning problems. It has done this by applying the powerful techniques of hierarchical planning and FRAME knowledge structures to an Air Show of Force action using a subset of the related military databases. Since KBS has the structure for expansion to more operationally realistic situtations, it can be modified to fit many military or crisis planning problems. KBS has the following advantages in a crisis action planning situation:

- Thorough consideration of all relevant factors
- The combined expertise of many expert military planners
- Prompt response to crisis situations
- Systems can be duplicated for dissemination
- Consistent behavior
- Privacy
- Adaptability to operator's preference
- Education of new planners.

KBS has not yet demonstrated that such a system can be implemented in an operational environment. The following risk areas remain:

- On-line access to the required data from the operational databases
- Incorporation of many additional military situations and details
- Use of pre-existing subplans
- Operational implementation language and hardware
- Full System performance.

In addition to the above risk areas, the following areas need to be completed:

- o Convenient, graphics user interface
- o Better plan evaluation
- o Easier entry of knowledge.

Recommendations

To demonstrate the utility of KBS and similar systems in the military planning environment, it will be necessary to involve these systems in actual military planning situations. Reduced scale databases and situations will improve the theoretical foundations of Artificial Intelligence Planning Systems; however, for users of military planning systems to be convinced that any new system is valuable, actual involvement of the system in realistic situations must be demonstrated. For these reasons, it is recommended that KBS be developed to the point that it can be used in a military planning exercise. This prototype version could then be used parallel to, and compared with, existing systems in a military exercise. To provide for quick development and minimum interference with existing systems, the system should be developed on a dedicated computer with strong graphics support. This development system would be interfaced to the military networks to provide it with access to the required data.

1.0 INTRODUCTION

Crisis situations within the military establishment frequently require prompt and secure planning of complex actions. These plans are subject to error because the time sensitive nature of the activity prevents consideration of all of the viable alternatives and precludes thorough investigation of the selected alternatives. Further, security considerations may prohibit crisis planners from having access to the specialized experts and data required to complete the plan. In addition, this planning activity is often carried out by staff officers with limited experience. These problems inherent in present crisis planning methods have the potential to produce plans inadequately adapted to the military situation and the locale of the crisis.

In an attempt to mitigate the effect of these difficulties, the authors have investigated the best use of automated decision aids to assist the planner. This document is a final report on this effort. Not only would these decision aids have access to a large number of facts relevant to the plans to be developed, but, more importantly, these decision aids would also contain, in part, the accumulated knowledge and expertise of the best military strategists. Using Knowledge Based Systems, a technique from the field of Artificial Intelligence (AI), MITRE has implemented a demonstration system (KBS) in which the planning procedures, rules of engagement and deployment, mission requirements, and "rules of thumb" are embedded in the knowledge base. Most of this knowledge was obtained from experienced military strategists through interviews and direct observation of their methods.

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A Knowledge Based System, also called an Expert System, is able to provide the assistance required to overcome many of the problems outlined above. Computer automation provides rapid access to a large body of facts for prompt and thorough crisis response planning. Of special note is the ability of KBS to use heuristic, ad hoc procedures and information obtained from experienced military strategists. Through these mechanisms, the system becomes a powerful, intelligent aid to the planner. Based on the rules obtained from the human expert, the system can make inferences through the successive application of several rules to solve problems (e.g., resolve plan deficiencies) through relatively standard procedures. On the other hand, Expert Systems do not perform well outside their domain of expertise. Also the current state of the art does not adequately support systems that attempt to learn or apply general principles to new situations. Thus, an Expert Crisis Planning System will perform well only in situations for which knowledge has been obtained and relevant facts are available.

The MITRE effort in this area started in 1977 as an internally funded research and development (IR&D) project oriented toward the preparation of accurate Crisis Action System (CAS) messages. A system was implemented in 1978 on a resource constrained computer system. Two lessons were learned from this effort. The first was that accurate message preparation and checking was not possible without substantial knowledge of the context (i.e., the situation) of the message. The second lesson was that the computational resources required were significant. Based on these lessons, it was decided that the project would deal with the full crisis response plan, as described above, and utilize more powerful computer resources. At the same time, an informal association with personnel of the Office of the Joint Chiefs of Staff (OJCS) was obtained. This allowed interaction with active crisis response planners. With this source of expertise and with Mission Oriented Investigations and Experimentation (MOIE) funding, development of a crisis response planning system (called KBS) was undertaken. This document is a report on that system.

1.2 System Goals

The primary goal for KBS was to provide a demonstration interactive system which would assist the staff officer in preparing a set of alternative plans in response to a crisis situation. Although KBS was seen as a potential Service-wide decision aid, it was recognized that the limited resources available for the development would severely restrict the scope of the effort. For these reasons, the crisis actions to be considered were limited to one scenario, an Air Show of Force, only extracts of the available data were used, and development of a sophisticated graphics user interface was deferred. The major goals, summarized below, were to:

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To describe KBS, it is convenient to use parts of specific plans and planning activity as examples. The following subsection describes the Air Show of Force scenario and the specific plans used as examples.

1.3 Scenario

To test and develop the algorithms used in the KBS program while avoiding the use of classified data, an Air Show of Force scenario has been developed around states in the Southwestern United States. In this scenario, the states are treated as hypothetical, friendly and unfriendly, independent countries. Given some basic parameters for decision-making (e.g., the location of the threat, the site for the Show of Force, the Forward Operating Base, and the number of aircraft required), KBS is prepared to plan a Show of Force deployment of aircraft from a supporting country to a Main Operating Base (MOB) in a threatened country.

The specific planning activity used as an example in the remainder of this document involves the hypothetical problem of Oregon threatening California with Texas providing support for California. Although California has many airbases to support a Show of Force mission, the bulk of the military force is stationed at airbases in Texas. To create difficult problems for KBS, the databases used show some of the California airbases with facilities removed. The intervening states may be neutral or hostile. The object of the planning exercise is to choose airbases in California from which the Show of Force mission can be conducted, to decide what kind of military hardware (aircraft) should be used for the show, and to plan the routes by which this hardware and its logistics support can reach the respective bases in California while avoiding hostile airspace. All of these decisions involve feasibility and risk considerations.

1.4 KBS Overview

KBS permits great flexibility in the Show of Force plan that is developed. There are many factors that control the choice of airbases, aircraft type, flight paths, logistics support, etc. These factors can be altered for each session. A typical session in which KBS develops a Show of Force plan to a respectable level of detail might take one hour. During this time, the military strategist will use the KBS program to explore and evaluate many plan options. Some of these options may ultimately be feasible. In some situations it may be necessary to bring in extra logistics to upgrade a base. KBS can recognize this requirement, locate the needed logistics packages, and specify transportation options. The military strategist has complete control over the approach to the problem and the degree to which he wishes to be involved in the details of the problem's solution. The military strategist can make every decision himself, or he may delegate all or part of the decision making process to the program. When questioned, the KBS program can explain every decision it has made. Furthermore, it can provide running commentary as it analyzes a problem, if this is desired.

KBS provides the user with many options in the planning procedure. For example, there are several ways of starting to plan a Show of Force. One might start by first choosing the airbases for the mission, one might start by choosing the aircraft type, or one might allow KBS to make both choices. The KBS program is equally comfortable with any of these approaches to the problem.

The data available to the KBS program, although not always numerically accurate, is representative of the kind of data that would be available to an operational system. The system has access to information about airbases, aircraft, logistics, materiel distribution, geography, and weather.

A brief summary of the technology base used in the KBS system is included in Section 2.0. Section 3.0 is a qualitative description of the system itself. The following section, 4.0, contains some examples of what the system does. Finally, an evaluation and recommendations are given.

2.0 TECHNOLOGY BASE

The KBS system is primarily based on existing technology from the field of Artificial Intelligence. Specifically, KBS draws from previous work on Knowledge Based Systems and FRAMES and from the recent work on Planning Systems. The latter work has been extended somewhat by KBS. The remainder of this section contains a brief outline of this technology base.

2.1 Knowledge Based Systems

The first successful Knowledge Based System was DENDRAL, developed by Feigenbaum at Stanford University in 1969.(1) This program used the heuristic rules developed by chemists to propose and verify the molecular structure of a class of organic compounds from mass spectroscopy and nuclear magnetic resonance data. The heuristic rules were used to select a few candidates from the hundreds of millions possible for verification by direct computation. The system performed better and faster than the expert chemists that provided the heuristic logic. It discovered, in fact, previously undetected errors and omissions in the literature.

DENDRAL encoded facts and heuristic logic in IF-THEN Rule form. That is, IF <a premise is true> THEN <an action is taken>. The premise can be any test of the data available and of the conclusions previously formed by some other rule. The actions include entering a conclusion in the data base and requesting more information. The rules are independent and will become active whenever the premise becomes true rather than in some predefined programmed sequence. Because of their rule structure, DENDRAL and other Knowledge Based Systems are sometimes called Rule Based Systems.

After the DENDRAL system, the Stanford group developed a treatment program for bacterial blood infections called MYCIN.(2) The heuristic knowledge for this program was obtained from a group of expert diagnosticians. On the average, MYCIN performs as well as a group of experts and better than individual experts. The program interacts with the physician in simple English to obtain data about the patient. It also has the useful capability of providing explanations for its conclusions and actions. DENDRAL and MYCIN are but the best known of several successful KBS systems.

2.2 FRAMES

All of the above systems were carefully constructed for limited and well-bounded problem domains. This was necessary, in part, due to the absence of a general, tractable method for organizing the knowledge and rules of the systems. One of the more promising approaches to this problem is the system of FRAMES.[3] FRAMES, first used for visual scene description, have been generalized to describe any well-known situation. A FRAME system is a set of interrelated templates describing part of some known type of situation. The templates contain semantic information that describes the essential characteristics of a situation but leave unspecified the details (SLOTS) that might be unique for a particular instance of that situation type. An important point is that a FRAME may contain default information and procedural constraints for its empty SLOTS; thus, the database itself can contain the heuristic rules which would automatically be invoked whenever data is entered or accessed.

FRAMES may be organized into a hierarchical structure with the more general and abstract information contained high in the FRAME hierarchy. Thus the FRAME for AIRCRAFT could contain information about all aircraft (such as: they fly, must take off and land, etc.). The frame for a specific aircraft need only contain the actual quantities (e.g., speed) and the interpretation is inherited from their ancestor frames. This type of knowledge base organization, which can be used to organize both information and rules (knowledge), provides a structure by which a KBS can deal with larger, less well defined problem areas.

2.3 Planning Systems

The systems decribed above are generally intended to obtain a specific answer to a problem and are not involved with specifying a temporal ordering of activities. Planning systems, however, must deal with temporal requirements, likely alternatives and incomplete solutions. A milestone effort in planning systems was the NOAH system of Sacerdoti.[4] The three key ideas of his work are:

a. The use of a plan hierarchy. This allows the step-by-step development of plans from a high level of abstraction to the final detailed plan so that the "major" decisions can be made first without considering the laborious details of the final plan.

b. Deferred time ordering. This allows the major components of the plan to be developed first so that their requirements and attributes may be used in determining the ordering and timing of plan actions.

c. Introspection and modification of plans. In this procedure, the system provides for any necessary correction of plans developed hierarchically without consideration of all the available detail. It is this key idea that makes the efficiencies of the previous two ideas practical.

All three of these ideas have been incorporated into the KBS system.

Stefik[5] describes the idea of introducing additional and more detailed constraints as the plan is expanded. KBS also developed this idea independently of, but later than, Stefik. While the constraints of Stefik's system (called MOLGEN) are binary and cause his system to disregard or prune some plans as impossible, those of KBS provide commentary on the plan and only indicate difficulties with some types of plans. The effect of this KBS commentary is to either improve or reduce the suitability of the particular plan choices being examined. Negative comments will trigger an attempt to satisfy the constraint at some later time in the planning process. Stefik also inferentially propagates constraints from the detailed considerations to the more abstract levels of the planning process. This allows high level pruning of the search tree based on low level constraints. This is very effective for planning systems operating in a domain in which a best plan exists and is identifiable. Since KBS is designed to produce a number of good alternative plans for external decision, it was not clear how this could have been safely done in KBS without the danger of eliminating an otherwise good plan because of a deficiency that could be corrected or ignored. In a companion paper(6) Stefik discusses the concept of layered control structures in which the more detailed rules of how to plan are introduced gradually as the details of the plan are developed. This concept is also used in KBS.

The next section provides a short description of the KBS system and its relationship to the technology base presented in this section.

3.0 SYSTEM DESCRIPTION

The primary objective of this project was to design and build an experimental Knowledge Based System (KBS) that could be demonstrated as a decision aid by military strategists for building, verifying, and rating plans for a military response to a crisis situation. The experimental KBS was used to illustrate the capabilities that KBS and AI technology could provide to those who work in the military planning environment. In order to test the capabilities of the KBS, the threat scenario described in Section 1.3 was created for the Southwestern United States. Data bases containing aircraft, airbase, logistics, geographic, and weather information were made available to the system. Rules for military planning and strategy were transcribed from conversations with members of the OJCS into computer format. The KBS was then used in an interactive mode to develop and analyze plans for a Show of Force response to crises in the Southwestern United States. These results were compared against plans proposed by members of the OJCS. The following subsections describe some of the capabilities of KBS and present a brief outline of the system design and implementation.

3.1 KBS Capabilities

KBS is a hierarchical planning system that generates plans by successive refinement of abstract versions of the plan. KBS, then, models the human planning process by developing first a set of possible alternatives and then filling out the details in a series of successive steps. Like humans, it will abandon alternatives when insurmountable difficulties are encountered and will generate new alternatives as needed. The remainder of this section describes in more detail some of the capabilities KBS provides in order to generate these plan alternatives.

3.1.1 Interactive Control

The KBS program is a highly interactive system. The dialog between the operator and the system may be quite extensive during the course of a planning session. The operator has control over the level of interaction in that he can suppress much of the system output and can allow the system to work independently on the plan. This mode of operation limits operator interaction to supplying the initial situation and mission description and to providing required data unavailable to KBS. On the other hand, the operator may require detailed notification of current KBS activity and may control each refinement step of the KBS planning activity. In this case, heavy operator involvement will occur. As KBS produces the detailed notification of its current activity, it prints on the terminal the different steps in its analysis. This can be very useful in showing a new operator that the system is making all the right considerations. As the operator becomes accustomed to KBS, much of this verbiage becomes unnecessary. The operator can then reduce the amount of "stream of consciousness" output that KBS produces. In addition to this involvement while the alternatives are being developed, the operator may request information about the plan and the reasons for choices made in the plan.

Interaction with KBS is through an alpha-numeric terminal using the KBS Command language. The Command Language provides a limited vocabulary of specific English words that the operator uses to direct the interactive Knowledge Based System. Examples of lines of Command Language input to KBS are given in Figure 3-1. Some of these examples are described below.

The "REFINE" commands instruct the system to prepare possible plan options and alternatives. The "TRY" commands assert a possible location, such as Mather or Travis, as values for plan variables. The "SHOW" commands invoke the interactive knowledge-based query

- WORK ON SHOW-OF-FORCE;
- TRY MATHER FOR BORDER;
- TRY TRAVIS FOR FORWARD-OPERATING-BASE;
- SET VERBOSITY 2;
- SHOW;
- REFINE AIRCRAFT-TYPE;
- SHOW ALL;
- SHOW DISTANCE FROM EDWARDS TO TRAVIS;
- WHY MAIN-OPERATING-BASE;
- WORK TO DEPTH 4;

FIGURE 3-1
COMMAND LANGUAGE EXAMPLES

capability of the Command Language. And the "WHY" commands ask the system to indicate the advisability of using Edwards AFB as the Main Operating Base. The "WORK" and "SET" commands control the amount of detail and explanation in the plan development.

The Command Language permits much more flexibility than a menu driven system but not as much as a Natural Language system. OJCS did not indicate sufficient interest in the extra capabilities of a Natural Language system over a Command Language system to justify the work necessary to create a Natural Language interface. The Command Language approach provides all the interactive capabilities that OJCS desired for the KBS program.

3.1.2 Arbitrary Problem Specification

Different military strategists will approach a given situation from different points of view. In the Show of Force scenario, one strategist might first specify the MOB and then determine the appropriate aircraft for the mission. Another strategist might first specify the aircraft for the mission and then determine the MOB to accommodate the aircraft. In fact both the MOB and aircraft may be left unspecified; then KBS would choose both from the set of all possible pairs of MOBs and aircraft types. Of numerous possible plan variables, the operator may know and specify in advance some, none, or all of their values. The system is able to analyze the problem in terms of the remaining unknown plan variables. If the plan variables are completely specified, then the system will just make the checks for consistency of the plan and report any deficiencies. Otherwise the system will suggest possible alternative values for the unspecified plan variables.

3.1.3 Analysis and Verification of Plans

The KBS system analyzes a plan by checking the feasibility of each of the plan steps. These checks are made by constraint rules invoked by the refinement of the plan steps or of a choice for a plan variable. Thus the checking software is called only when there is sufficient information to make the check. Some checking can occur while the plan variables have abstract values. As each plan becomes more detailed, more checks come into play to verify the feasibility of the plan. For example, initially the system checks that the Main Operating Base is approxiamtely 200 miles from the threat border. After some refinement (e.g., selection of aircraft), the system will automatically check the feasibility of an airbase to accommodate the take-off and landing of aircraft being considered for a Show of Force. This means checking the length of the runways, the width of the runways, the loading capacity of the runways, the availability of taxiways, hangar space, and maintenance facilities. Also, there are communication, navigation, fuel availability, and strategic considerations for the choice of the airbase.

The result of this checking is a list of comments for each choice made in the plan. These comments indicate the failure or success of the constraint and describe the type of constraint and the degree of failure. For example, a comment would indicate failure of a constraint if the runway were too short, but, in addition, the comment would provide the reason for and amount of the failure. This commentary is used by KBS to guide its search for alternatives and to rate the various alternatives found. As shown in Section 4.6, this commentary is also available to the operator.

3.1.4 Augmentation of Plans to Correct Deficiencies

As the checking described in Section 3.1.3 proceeds to more detail, it is likely that a heretofore unseen deficiency will be discovered. At this point, KBS, like the human planner, has several options.

- A correction attempt may be made
- The alternative may be abandoned
- The deficiency may be ignored

Whenever possible, KBS will attempt to correct the deficiency by generating additional plan steps. KBS uses the informational part of the negative commentary to plan a corrective activity. For example, if a proposed MOB is discovered not to have sufficient navigational aids, KBS will locate the appropriate installation kits and arrange for their transportation and installation. If correction is not possible, KBS will either abandon the alternative or ignore the deficiency depending on the severity of the comment and any appropriate knowledge rules. At any time, the operator can instruct KBS to ignore the negative comment.

3.1.5 Simultaneous Developemnt of Multiple Plans

The KBS program switches its analytical capabilities back and forth among several concurrent alternative plans. To the operator it appears that KBS is analyzing all plans simultaneously. The KBS program allocates its computational resources to several plans based on the amount of perceived difficulty in making each plan feasible. Plans that have many negative comments are allocated less computer effort. Thus, potential plans that seem most readily feasible receive immediate attention. Due to the subsequent invocation of additional constraints as the plans are refined, it is possible for initially unlikely alternatives to have greater feasibility, finally, than those alternatives that at first appeared most promising. For this reason, KBS continues to examine each potential alternative, even if unlikely, so that the optimal plans are designated. Also, new alternatives will be examined even though perfectly good alternatives have previously been discovered. This heuristic search of the problem space insures that the system can identify optimal plans even though they are not initially promising, and it prevents the system from concentrating exclusively on plans that are initially promising but have some hidden major difficulty that is unrecognized until later in the analysis. The result of this simultaneous development is a list of prioritized options for consideration by the operator.

3.1.6 Partially Specified Plans

A partial plan is a plan for which all of the details have not been completed. From the point of view of KBS, partial plans are the natural result of KBS not completing all of its plan steps. In the larger sense, the partial plan may be the end result of a OJCS planning effort as transmitted to lower commands for completion. KBS will work to any depth desired by the operator and present the (partial) plans that result from this effort. KBS may be instructed to resume work on any designated set of partial plans. Partial plans are useful to the operator if only a high level feasibility estimate is required or if time does not allow the additional refinement.

3.2 Design Objectives

The basic design objective was to apply the best technology from the fields of Artificial Intelligence and software development to attaining the System Goals of Section 1.2. It was recognized that the demonstration system would be evolving as more knowledge was attained and as the applications changed. For this reason, flexibility was given precedence over performance. In addition to the Knowledge Based, FRAME and Planning technologies discussed in Section 2.0, the following design goals deserve special mention.

- o The system should have a Command Language for easy Man-Machine interaction.

- o The system should rank options based on their difficulty of execution. It should present the best options first.

- The system should provide, upon request, a "Stream of Consciousness" to indicate all the checks that the system is making in an analysis.

- The system should be capable of heuristic searching based on the expected rating of the various alternatives. This implies an ability to switch among several potential solutions to a problem as the estimate of their merit changes.

- The system should act as a filter between the database and the operator, by presenting to the operator only the relevant information.

- The system should be able to use logic. Specifically the system should be able to infer specific facts about an object from properties of more general representations of the object.

- The system should provide a representation for knowledge which is sufficiently general to accommodate the wide range of knowledge about airbases, aircraft, geography, weather, logistics, plan operations, sub-plans, feasible options, plan constraints, and methods for choosing alternatives.

3.3 System Architecture

The architecture of the KBS program, illustrated in Figure 3-2, is composed of intelligent software and knowledge. The knowledge is in the form of a FRAMES database, a geographic database, and a library of rules. The FRAMES database contains symbolic and numeric facts about objects such as aircraft, airbases, and logistics kits. The geographic database permits the retrieval of information based on geographic proximity. Rules are a more potent form of knowledge composed of a template and a body. If the formulation of a plan step can be matched to the template of a rule, then the body of the rule can be applied toward the development of the plan step. The body of the rule can be a routine for generating options, an evaluation function, or a plan step template depending on whether the rule is an expert, constraint, or plan method respectively.

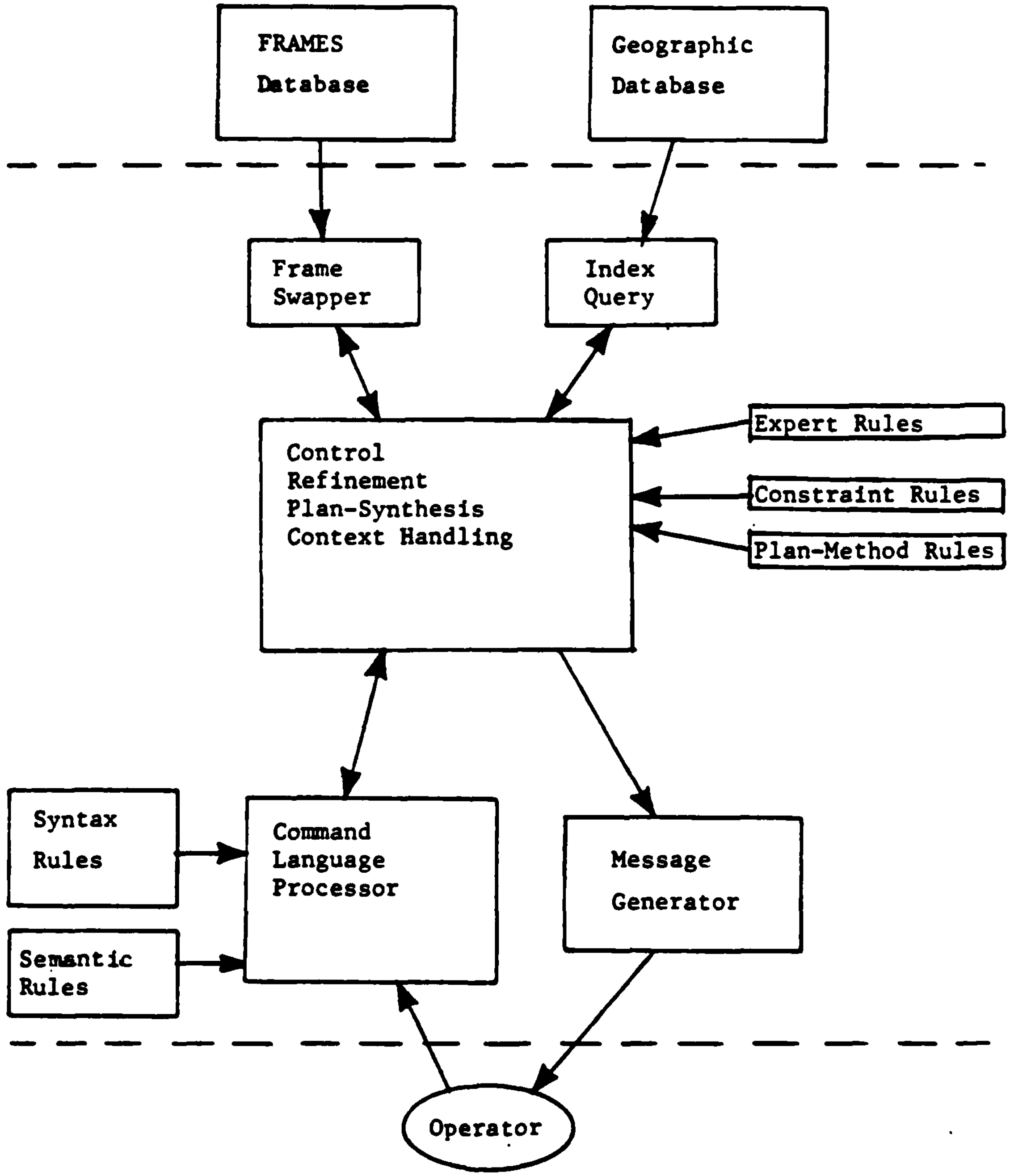


FIGURE 3-2
SYSTEM ARCHITECTURE

The intelligent software uses guidance from the operator, knowledge contained in the rules, and information in the databases to control the synthesis of plans. Since numerous plans and their alternatives may be under consideration at any given point in time, the system needs a method of switching its computational effort from one plan to another. This is accomplished with context handling software.

In addition there are several other software modules that allow KBS to communicate with the operator and the databases. The Command Language Processor translates operator commands in a language defined by syntax and semantic rules into a data structure that can be used by the intelligent software. All input by the operator goes through the Command Language Processor. Messages from KBS are translated back into operator readable form by the Message Generator. Many of the FRAMES are large data structures and are transferred from disk to core only when the system is actively using the information. The FRAME Swapper automatically controls which FRAMES are in core at any given time.

The generality of the KBS architecture permits KBS to be modified to operate on any kind of planning problem by simply replacing the expert, constraint, and plan method rules with domain specific knowledge for a different planning problem. Furthermore, the Command Language can be quickly adapted to accommodate new commands, different syntax, or different semantics by changing the syntax and semantics rules. The KBS rules are a dynamic part of the program. Changes and additions to the rules are made quite frequently as the system is enhanced.

3.4 KBS Implementation

The implementation of KBS is based on the INTERLISP System[7] augmented by the Frame Representation Language (FRL)[8]. The

INTERLISP System supports a dialect of the LISP language as well as a number of powerful user services (e.g., a file package, a structure editor, etc.). LISP is a popular list processing language well-suited to Artificial Intelligence software development. FRL is implemented in LISP and provides the requried tools to support FRAMES. The remainder of this section contains discussions of several significant design and implementation aspects of KBS.

3.4.1 Knowledge Representation

The KBS demonstration system is required to utilize many different kinds of knowledge. For the purposes of KBS, this knowledge has been organized into three categories.

- o Facts (e.g., airbases, aircraft, weather, etc.)
- o Planning Methods and Constraints
- o Plans

Each of these knowledge catagories has its own internal representational data structures. Facts are stored in the FRAMES data structure. Much of this information is symbolic and numeric rather than procedural. Knowledge about the selection of plan steps and plan variables is stored in RULES, and, finally, knowledge about specific developed plans is stored in the PLAN-TREE data structure.

3.4.1.1 Facts Data Structure. For KBS facts are organized within the FRAME mechanism in a hierarchical structure. Thus, FRAMES are used to represent both abstract and specific objects. An example of the FRAME organization for facts is illustrated in Figure 3-3. There are FRAMES for F-4, F-15, F-111, C-5, C-130, and C-141 aircraft. The SLOTS of each FRAME contain information relevant to that type of aircraft, such as range, weight, and wingspan as in Figure 3-4. In addition, the cargo aircraft have SLOTS for cargo capacity (weight and volume). On the other hand, the fighter aircraft have

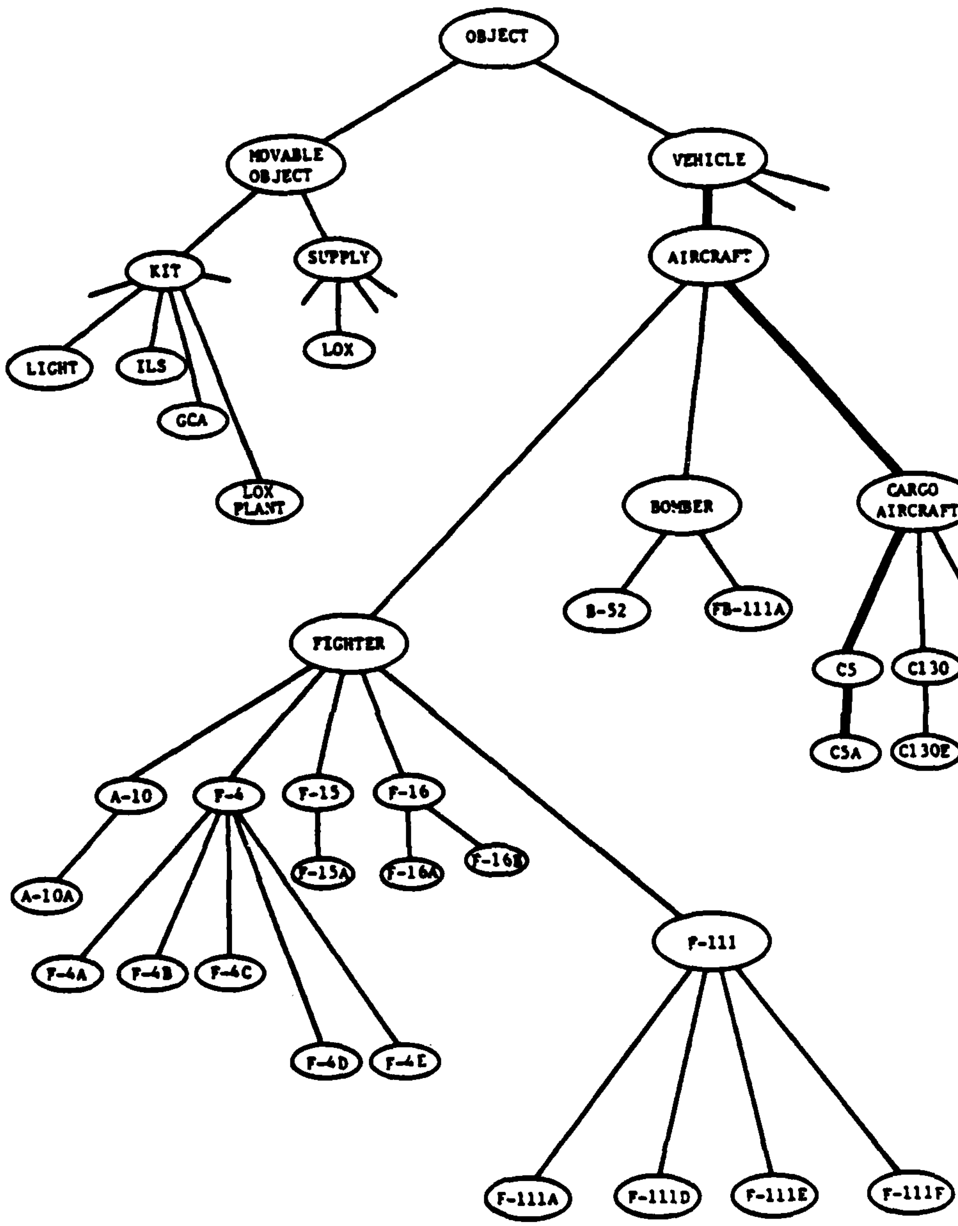


FIGURE 3-3
FRAME HIERARCHY

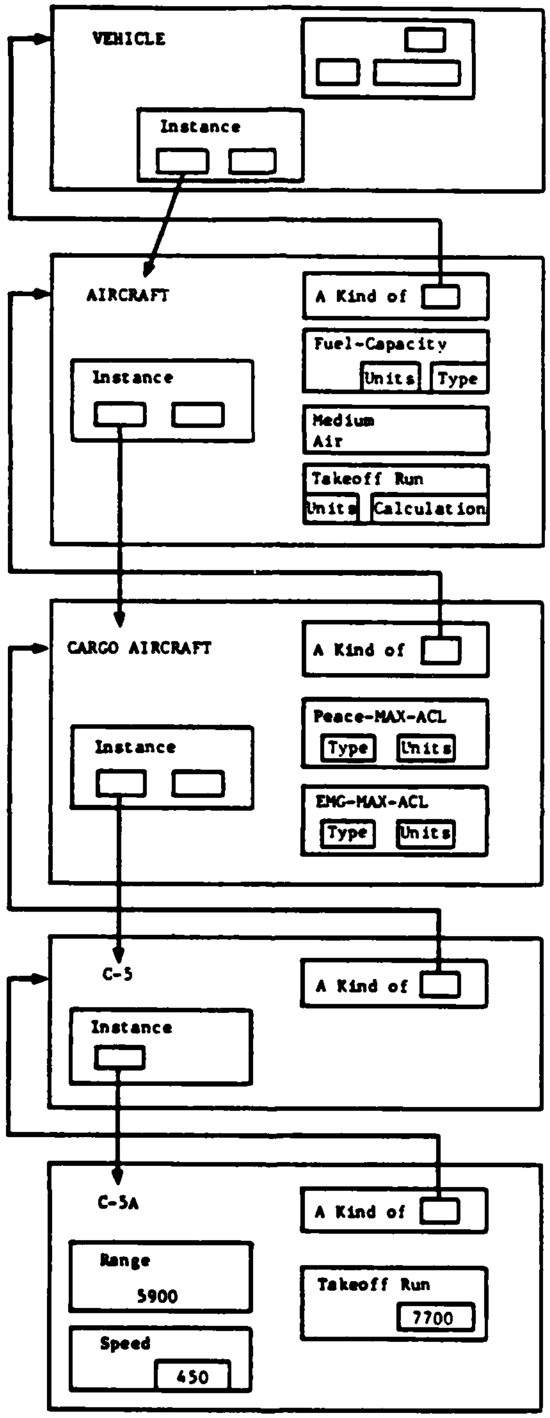


FIGURE 3-4
FRAME DETAILS

specialized SLOTS for flight dynamics and ammunition capacity. These are relatively specific FRAMES. There are also more general FRAMES for FIGHTER, CARGO-AIRCRAFT, and AIRCRAFT. Thus these three more general FRAMES are higher in the FRAME hierarchy. FIGHTER and CARGO-AIRCRAFT are descendants of AIRCRAFT. F-4, F-15, and F-111 are descendants of FIGHTER, and C-5, C-130, and C-141 are descendants of CARGO-AIRCRAFT. FRAMES can inherit information from SLOTS of their ancestors. The fact that an F-111 has wings and flies in the air is recorded in the AIRCRAFT FRAME because this attribute is common to all aircraft (helicopters and lighter-than-air craft have been excluded). This reduces significantly the amount of space required since duplication of a SLOT for each aircraft can be avoided.

3.4.1.2 Methods and Constraints Data Structure. The system uses a data structure called a "rule" to encode knowledge about building plans. Rules have a template and a body. If the template matches a given plan step specification, then the body of the rule is applied to the plan step. Each application of a rule moves the system one step closer to developing a plan. There are three kinds of rules: experts, constraints and plan methods. Expert rules generate sequences of potential values for plan variables and plan methods. This process causes the plan to become more detailed. The body of the expert rule is a subroutine that can return successive solutions to a small problem by using local rule-of-thumb knowledge. Experts are discussed further in Section 3.4.2. Constraint rules determine if a plan is feasible. "An airbase must have runways long enough to accommodate incoming aircraft" is an example of a constraint. Constraint rules are like expert rules except that the body of the rule is an evaluation routine that reports success or failure along with the reasons.

Plan method rules indicate the options and, within each option, the plan steps and plan variables required to accomplish a plan step.

The body of a plan method rule is the outline for the plan step. Figure 3-5 is an illustration of the OBTAIN plan method. The goal is to obtain some item at some destination. When this plan method is envoked, some details would be provided for these two plan variables. The OBTAIN plan method has four options:

- o If an item is already at the destination then no action is required.
- o The CONSTRUCT option is used if the item is to be built from parts at the destination. This could be used when obtaining a building or bridge.
- o The TRANSFER option is used if the item can move under its own power from its current location to the destination. This option is used for obtaining aircraft that can fly to the destination.
- o The TRANSPORT option is used for items that must be transported as cargo from their source to the destination.

New plan variables are introduced by each option. For example, if the TRANSFER option is selected, a Source plan variable is introduced. It should be noted that the OBTAIN plan method is reinvoked as a plan step in the TRANSPORT option.

Each option in a plan method may contain expert and constraint rules. These are illustrated in Figure 3-5 by the clouds and hexagons attached to the option name. This is the mechanism by which experts and constraints are introduced at the appropriate level of detail.

3.4.1.3 Plan Data Structures. Plans are composed of plan steps and alternatives to form a plan tree. At the root of the plan tree is a single plan step describing the action to be planned. Each plan step is satisfied by a sequence of additional plan steps. The process of refinement expands a designated plan step into the plan steps required. It is seen then that the levels of the plan tree represent different levels of abstraction of the plan. Higher levels

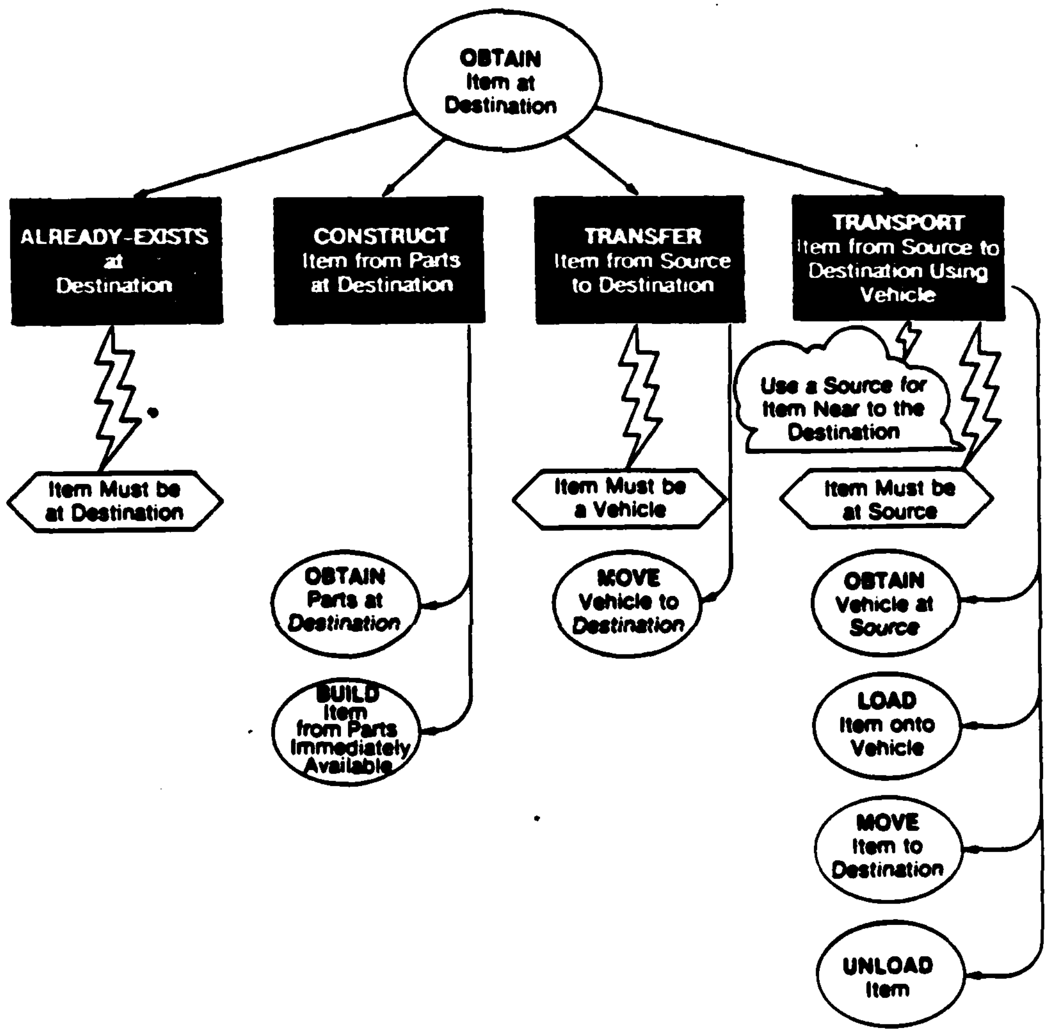


FIGURE 3-5
OBTAIN PLAN METHOD

of abstraction are closer to the root of the plan tree. Figure 3-6 illustrates an example of a plan tree. In this case, the root of the plan tree is the SHOW-of-FORCE plan step. The results of plan step refinements are shown along with an indication of the level of abstraction. The values of the plan variables and their interrelationships among the plan steps are not shown.

Plans in KBS must contain alternatives. These alternatives exist both in the option selected from the plan method and in the values selected for the plan variables. These alternatives are contained in the plan tree as additional branches from each plan step. Graphical representation of this complication is not helpful.

The previous section described plan methods as templates for plan steps. Figure 3-7 shows an OBTAIN plan step extracted from a plan tree. This plan step was generated in order to correct a navigation aid deficiency at China Lake airbase. Note that the TRANSPORT option was selected and that many of the plan variables have been specified.

3.4.2 Experts

The KBS program uses numerous expert rules to help solve planning problems. Each expert uses self-contained heuristic and rule-of-thumb knowledge to solve problems like the refinement of plan variables or selection of plan method options. Since each expert suggests values for a plan variable or option based on a simplified model of the problem, each choice must be carefully checked by the remainder of the KBS program. This is done by activating the appropriate constraint rules. If the proposed value causes a difficulty and when additional options are being explored, the expert may be reinvoked to suggest a second best value. The expert may continue to be invoked in this manner to provide further values. Experts will continue to return proposed values until every possible value has

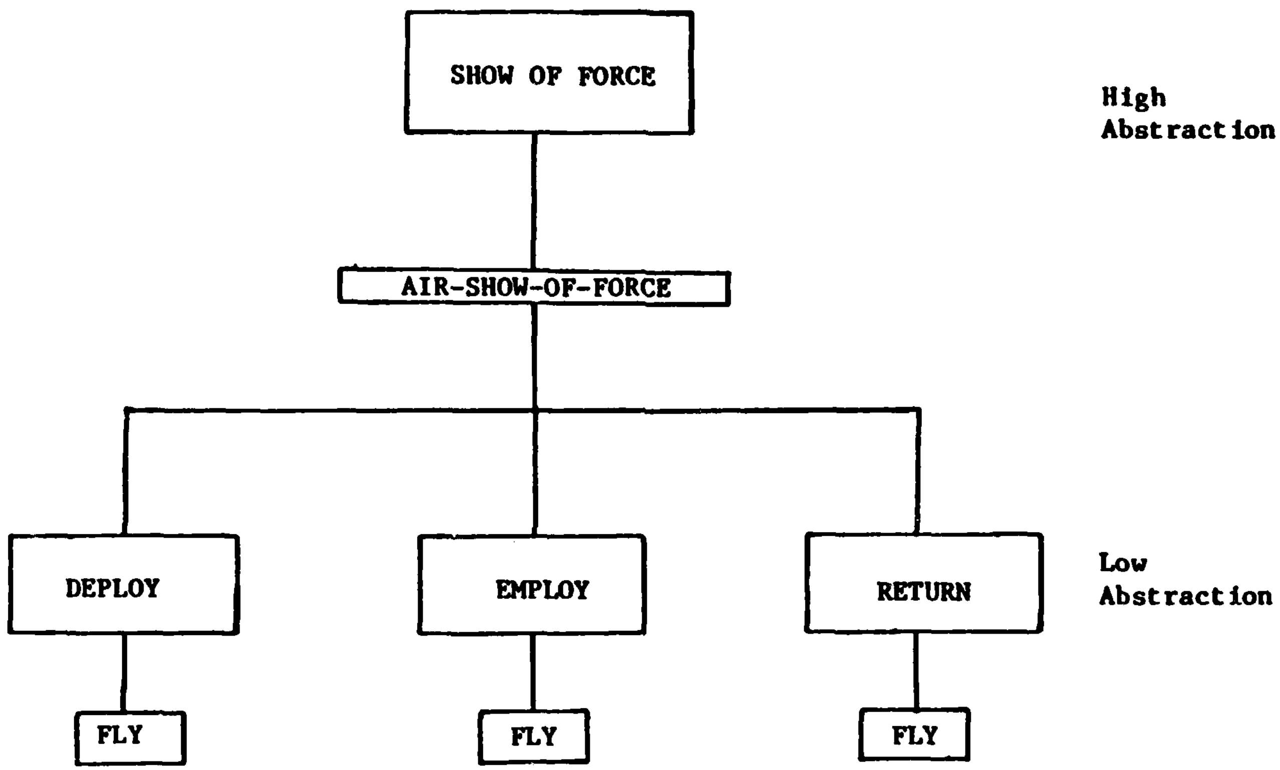


FIGURE 3-6
SIMPLIFIED PLAN TREE

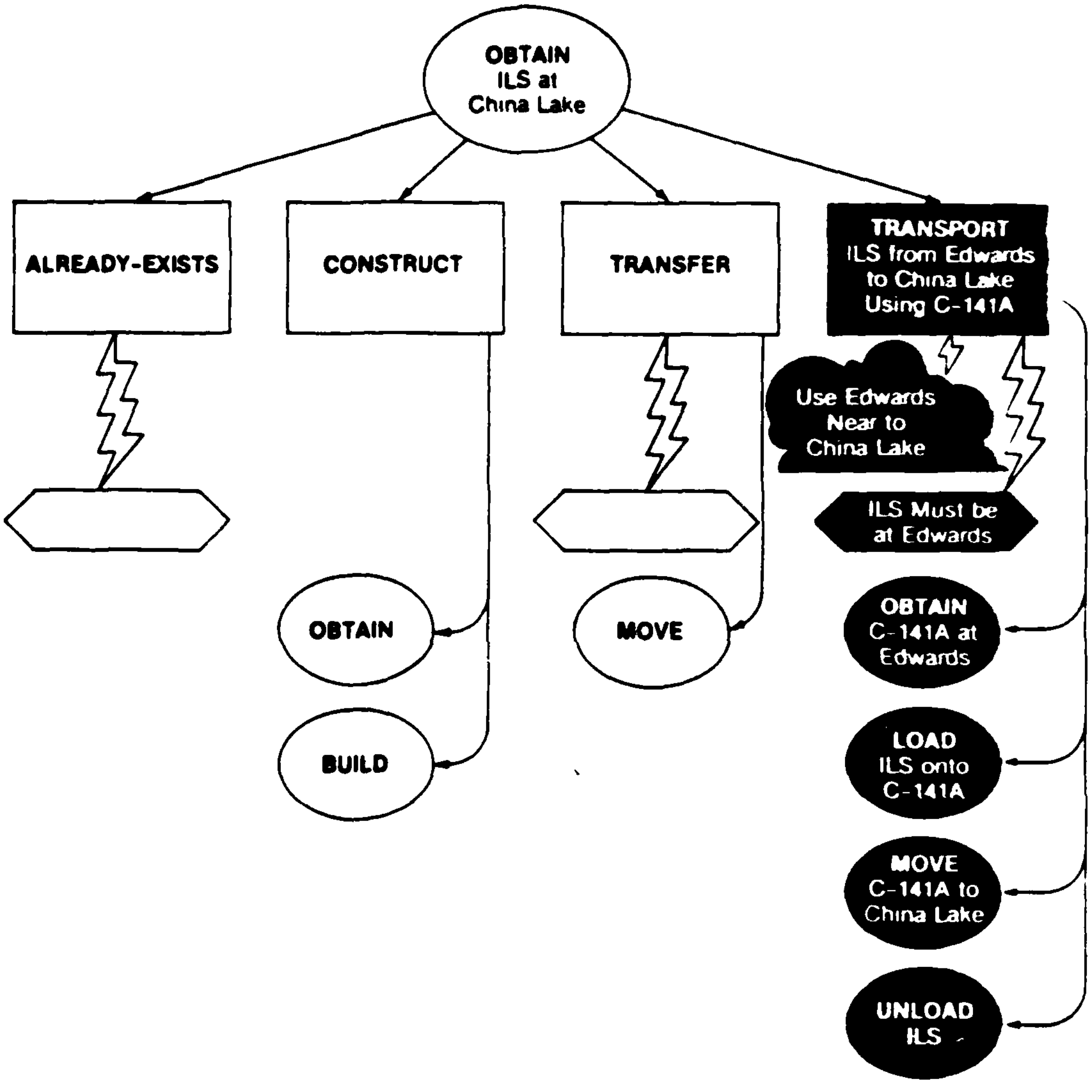


FIGURE 3-7
SPECIFIC INSTANCE OF OBTAIN PLAN-TREE

been explored. These expert rules are composed of matching templates and generator routines. When a particular problem formulation matches the template of some expert, that generator routine is called to generate a locally optimal solution to the problem.

In the example illustrated in Figure 3-8, the expert contains the knowledge that the Main Operating Base (MOB) should be as close as possible to the Forward Operating Base (FOB), but it should not be much closer than 200 miles, to the BORDER. Initially the expert suggests airbase C for the MOB since C is the nearest airbase to the FOB which is further than 200 miles from the BORDER. Airbase C is only a suggestion, and the KBS program or the operator may reject this suggestion based on other knowledge not available to the expert in this example. If C is rejected, then the expert will suggest using D for the MOB. This is the second best choice according to the expert's heuristic knowledge. If this possibility is rejected the expert will continue in this manner to suggest successively less optimal solutions to the MOB problem, until all possible airbases have been examined.

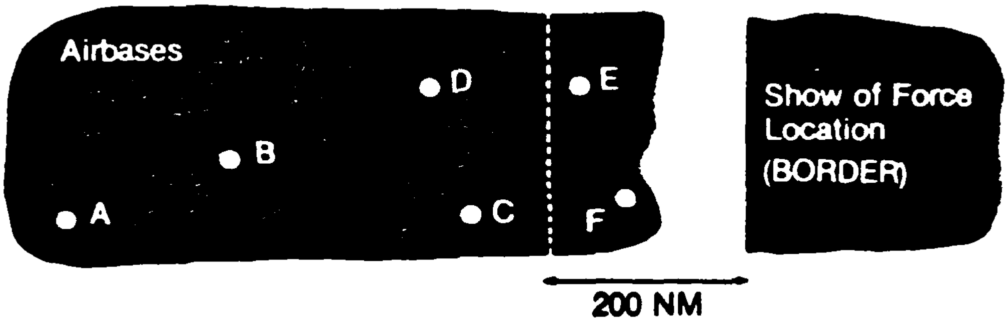
When a problem has many feasible solutions, the solution which is optimal in the global domain will almost certainly be different from the solution obtained from optimizing in the local domain. On the other hand, it is anticipated that the globally optimal solution will be one of the early suggestions for the locally optimal solution. The use of experts, then, constitutes a heuristic method for searching the solution space for good solutions. It is highly likely that several good solutions will be found early in the process.

3.4.3 Control Structure

The control structure of KBS controls the expansion of the plan tree in response to the operator's commands. Based on the output of the experts and constraints, the control structure rates the various

A KBS Expert is a subroutine containing rule-of-thumb knowledge that suggests refinements of plan variables.

A Show of Force Scenario



A KBS Expert would use knowledge of the appropriate distance between a Main Operating Base and the Show of Force Location to suggest sequentially the use of airbases (in the order of C, D, E, B, A, and finally F) as the Main Operating Base for a mission.

FIGURE 3-8
A KBS EXPERT

alternatives and, when working without direct operator control, selects the various alternatives and plan steps for refinement. Negative comments are analyzed and corrective plan steps are created if reasonable.

Examples of plan trees, the actions of the control structure and other system capabilities are in the next section.

4.0 KBS EXAMPLES

This section presents some examples of KBS operation. These are demonstrated capabilities and are illustrated by excerpts from actual runs of the system. These runs are all based on the scenario of a Show of Force in northern California, supported by Texas, as described in Section 1.3. In the specific situation that is illustrated, the operator has specified Mather as the Border, Travis as the Forward Operating Base, A-10 as the aircraft class, Nevada and New Mexico as the No Overflight Areas, and 25 as the number of sorties to be flown each day. KBS has been run to select alternatives for the Main Operating Base and the acquisition of specific aircraft. The examples shown describe a plan and the alternatives along with the result of the operator changing a plan variable. Also included are a display of reasons and data from the knowledge base, an example of negative commentary with the resultant corrective plan steps, and a crude map of the situation. Since KBS output is to a teletype terminal, it was necessary to augment some of the examples with manually created figures for additional clarity.

4.1 Development of a Hierarchically Organized Plan

KBS develops plans in a hierarchical, top down manner, and stores them in a plan tree data structure. Each node in this structure is a plan step of a named type, with named plan variables which give the specific information. Figure 4-1 shows a simple plan in outline form. This figure consists of actual output from the system, slightly shortened and edited for clarity. Figure 4-2 illustrates more clearly the tree structure of this plan. In this plan, KBS has chosen Edwards as the Main Operating Base and an A-10A as the specific aircraft. Each plan step is represented by a section in the outline, which is headed by the type of the plan step (such as "AIR-SHOW-OF-FORCE" or "FLY"). This is followed by a list of the plan variables of the plan step at that level and their corresponding

```
AIR-SHOW-OF-FORCE
   FORWARD-OPERATING-BASE = TRAVIS
   BORDER                 = MATHER
   MAIN-OPERATING-BASE    = EDWARDS
   AIRCRAFT-TYPE          = A-10A
   SORTIES-PER-DAY        = 25
   TOTAL-NUMBER-OF-PLANES = 13
   NO-OVERFLIGHT-AREAS    = list consisting of NEVADA
                               and NEW-MEXICO
Expansion
   DEPLOY  = OBTAIN
         MATERIEL = group of 13 of A-10A  's
         LOCATION = EDWARDS
         SOURCE   = ELLINGTON
      Expansion
         HOW = FLY
            VEHICLE             = group of 13 of A-10A 's
            ORIGIN              = ELLINGTON
            DESTINATION         = EDWARDS
            NO-OVERFLIGHT-AREAS = list consisting of
                                NEVADA and NEW-MEXICO
            ROUTE               = list consisting of
                      (29.6,-95.15) and (31.34,-109.048)
                      and (34.9,-117.8667)
   EMPLOY  = FLY-MISSION
         PLANES        = group of 13 of A-10A  's
         BASE-LOCATION = EDWARDS
         TARGET        = TRAVIS
         FREQUENCY     = 25
   RESTORE = REDEPLOY
         MATERIEL    = group of 13 of A-10A  's
         LOCATION    = EDWARDS
         ORIGIN      = ELLINGTON
         DESTINATION = ELLINGTON
      Expansion
         HOW = FLY
```

FIGURE 4-1
OUTLINE DISPLAY OF A PLAN (EDITED EXCERPT)

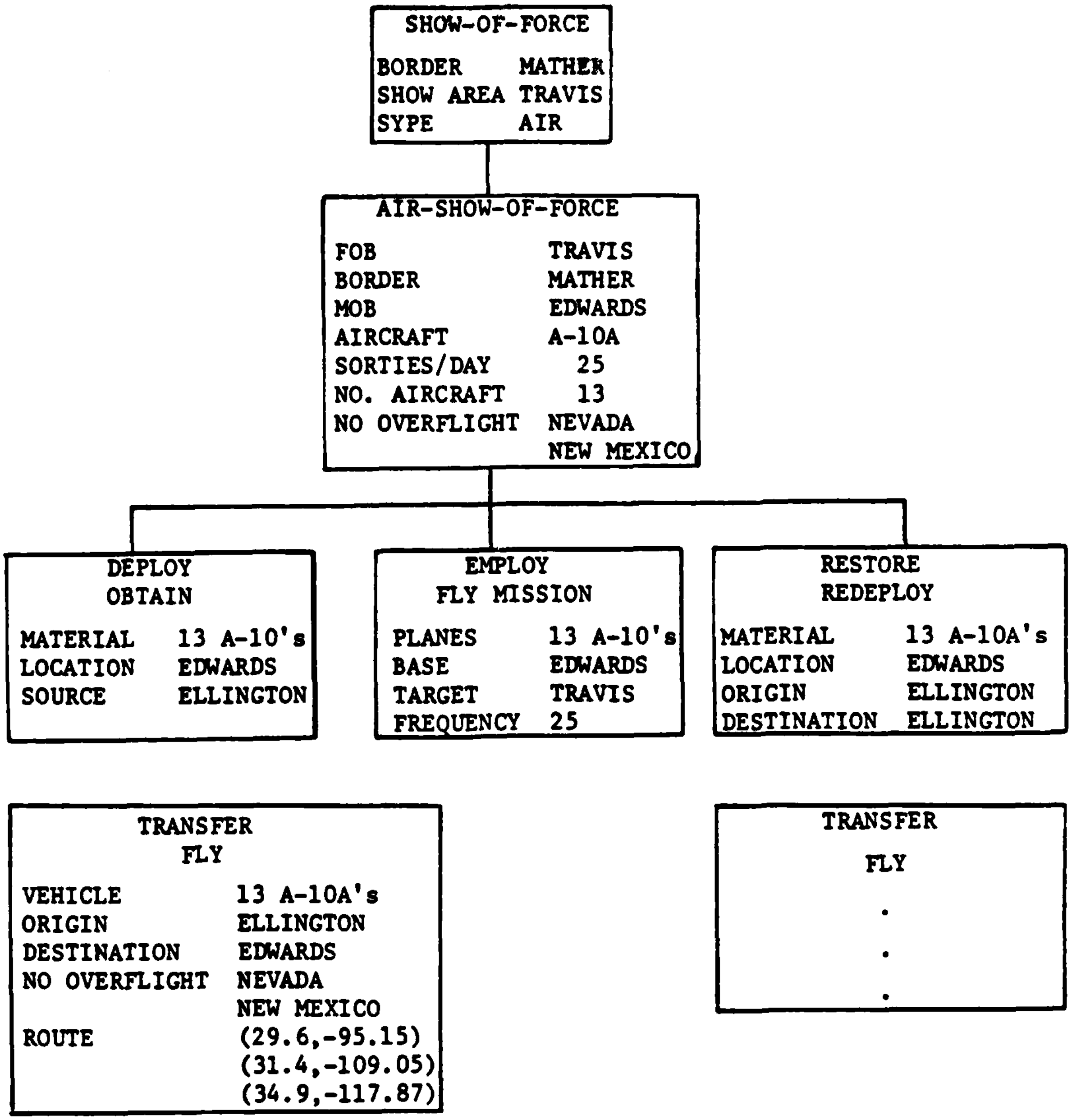


FIGURE 4-2
PLAN STRUCTURE

values. This is followed in turn by further plan steps of the plan, appropriately indented. These further plan steps are set off by the word "Expansion". In addition, each plan step is identified by a name indicating the purpose of the particular plan step. The three plan steps of an AIR-SHOW-OF-FORCE, for example, are named "DEPLOY", "EMPLOY", and "RESTORE". Where there is only one plan step, it is usually just called "HOW".

4.2 Changing an Existing Plan

After reviewing a plan developed using KBS, the operator may wish to make some changes. It would be inadequate to simply replace the values of the plan variables because the changes might result in constraints being violated. Rather, KBS must recheck all affected constraints and reconsider all choices which depend upon the one(s) which the operator is changing. The result of this process is shown in Figure 4-3. In this figure, the operator simply requested KBS to substitute F-111As for A-10As in the plan of Figure 4-1. KBS determined that Edwards was still suitable as a MOB, recognized the need to find a different source for the new type of aircraft (that is, BERGSTROM instead of ELLINGTON in this case), and made the appropriate changes. Note that new flight paths are also required and have been supplied.

4.3 Displaying Alternative Plans

One facility provided by KBS is a display of the alternative plans. Figure 4-4 shows such a display. Again, this is actual output from KBS, slightly edited. The information in this figure is displayed more accessibly and graphically in the manually created Figure 4-5.

Each typed line of Figure 4-4 represents one choice. The choice of a value for a plan variable is represented by a line containing the name of the plan variable, followed by an equals sign and the

```
AIR-SHOW-OF-FORCE
   BORDER                  = Ok  MATHER
   FORWARD-OPERATING-BASE = Ok  TRAVIS
   MAIN-OPERATING-BASE    = Ok  EDWARDS
   AIRCRAFT-TYPE          = Ok  F-111A
   SORTIES-PER-DAY        =     25
   TOTAL-NUMBER-OF-PLANES = Ok  13
   NO-OVERFLIGHT-AREAS    =     list consisting of
                  NEVADA  and NEW-MEXICO
Expansion
   DEPLOY  = OBTAIN
         MATERIEL = Ok  group of 13 of F-111A  's
         LOCATION = Ok  EDWARDS
         SOURCE   = Ok  BERGSTROM
      Expansion
         HOW = FLY
               VEHICLE              = Ok  group of 13 of F-111A  's
               ORIGIN               = Ok  BERGSTROM
               DESTINATION          = Ok  EDWARDS
               NO-OVERFLIGHT-AREAS =     list consisting of
                           NEVADA  and NEW-MEXICO
               ROUTE                = Ok  list
              consisting of (30.18333,-97.66667) and
              (31.34,-109.048)  and (34.9,-117.8667)
    EMPLOY  = FLY-MISSION
         PLANES        = Ok  group of 13 of F-111A  's
         BASE-LOCATION = Ok  EDWARDS
         TARGET        = Ok  TRAVIS
         FREQUENCY     =     25
   RESTORE = REDEPLOY
         MATERIEL    = Ok  group of 13 of F-111A  's
         LOCATION    = Ok  EDWARDS
         ORIGIN      = Ok  BERGSTROM
         DESTINATION = Ok  BERGSTROM
```

FIGURE 4-3
CHANGING AN EXISTING PLAN (EDITED EXCERPT)

```
SORTIES-PER-DAY = 25
MAINPOINT^
  NO-OVERFLIGHT-AREAS = list consisting of NEVADA  and NEW-MEXICO
    MAIN-OPERATING-BASE = CHINA-LAKE
      Criticism -> HOW=OBTAIN
        Criticism -> HOW=OBTAIN
OPTION5.^
    MAIN-OPERATING-BASE = EDWARDS
      AIR-SHOW-OF-FORCE -> DEPLOY=OBTAIN EMPLOY=FLY-MISSION
                           RESTORE=REDEPLOY
        AIRCRAFT-TYPE = A-10A
          TOTAL-NUMBER-OF-PLANES = 13
            OBTAIN -> HOW=FLY
              FORCE-ORIGIN = ELLINGTON
                ROUTE = list consisting of (29.6,-95.15) and
                     (31.34,-109.048) and (34.9,-117.8667)
                  REDEPLOY -> HOW=FLY
                    FORCE-ULTIMATE-DESTINATION = ELLINGTON
                      ROUTE = list consisting of (34.9,-117.8667)
                     and (31.34,-109.048)  and (29.6,-95.15)
OPTION1...............^
                ROUTE = list consisting of (29.6,-95.15) and
                     (37.0,-103.0) and (37.0,-109.048) and
                     (35.02,-114.612) and (34.9,-117.8667)
                  REDEPLOY -> HOW=FLY
                    FORCE-ULTIMATE-DESTINATION = ELLINGTON
OPTION2.............^
    MAIN-OPERATING-BASE = POINT-MUGU
    MAIN-OPERATING-BASE = GEORGE
      AIR-SHOW-OF-FORCE -> DEPLOY=OBTAIN EMPLOY=FLY-MISSION
                           RESTORE=REDEPLOY
        AIRCRAFT-TYPE = A-10A
          TOTAL-NUMBER-OF-PLANES = 13
            OBTAIN -> HOW=FLY
              FORCE-ORIGIN = ELLINGTON
                ROUTE = list consisting of (29.6,-95.15) and
                      (31.34,-109.048) and (34.58333,-117.3833)
                  REDEPLOY -> HOW=FLY
                    FORCE-ULTIMATE-DESTINATION = ELLINGTON
OPTION3.............^
    MAIN-OPERATING-BASE = SAN-NICOLAS-ISLAND
OPTION6^
    MAIN-OPERATING-BASE = NORTON
OPTION4^
```

FIGURE 4-4
DISPLAY OF ALTERNATIVE CHOICES (EDITED EXCERPT)

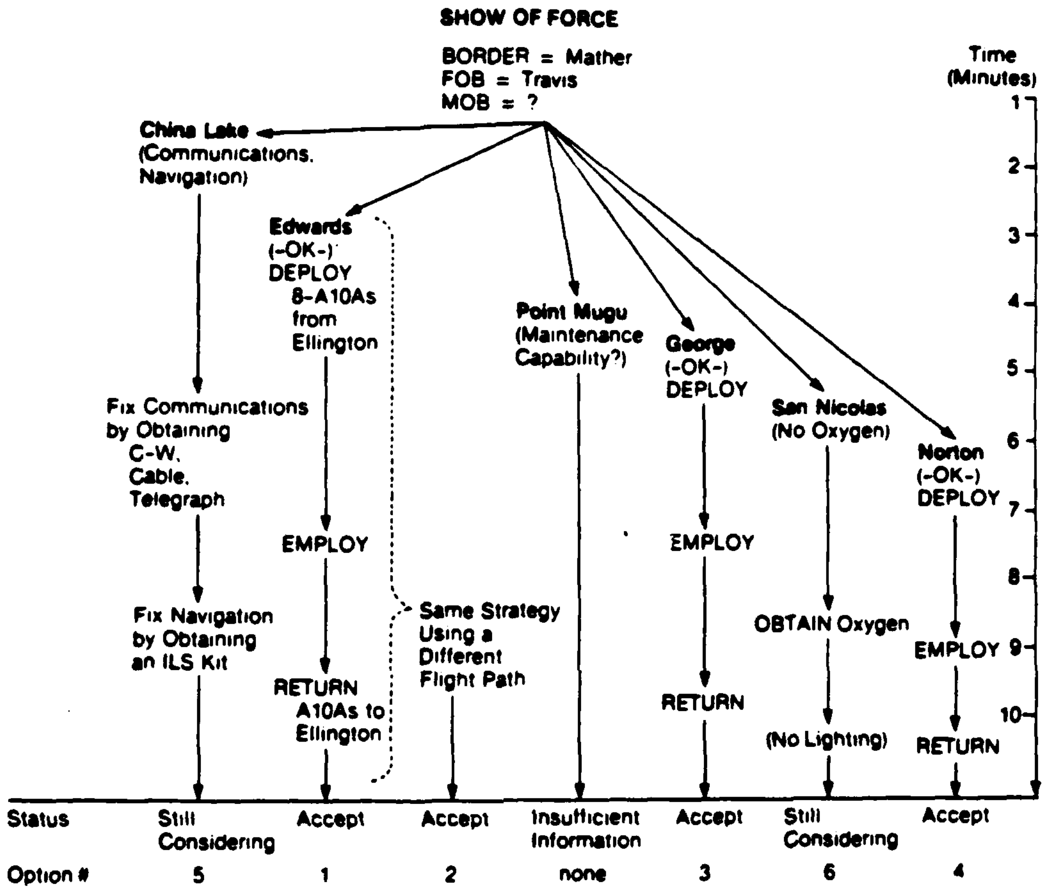


FIGURE 4-5
GRAPHIC DISPLAY OF ALTERNATIVE CHOICES

value. The choice of a method for implementing a plan step is represented by a line containing the type of the plan step being implemented (or "expanded"), an arrow ("->") and the named required plan steps. Where the word "Criticism" appears at the beginning of a line, it means that KBS has tried to correct a difficulty; the method for this correction is then displayed on the rest of the line in a manner similar to the expansion of a plan step into other plan steps.

Periodically throughout this display there appear lines consisting of a single name, followed by a line of dots, and ending with an upward-pointing arrow (e.g.. OPTION1.....^). These identify labels. The labels "OPTIONn", where "n" is a number, are plan alternative names assigned by KBS in the order in which it proposes them. Therefore OPTION1 is regarded by KBS as the best alternative, OPTION2 as the next best, and so on. OPTION1 labels the plan which was displayed in outline form in Figure 4-1.

As best seen in Figure 4-5, KBS accepts some alternatives and defers others. This evaluation is based on the difficulties encountered in expanding the alternative and the extent to which the alternative has been expanded. Since KBS attempts to discover several good alternatives, it continues to examine additional candidate MOBs even though it has found nothing wrong with Edwards.

4.4 Selective Display of Alternative Plans

The display just described is verbose and not very clear. To complement it, KBS also provides a selective display. To use this feature, the operator issues a command containing a selection criterion in the form of a logical expression. This is shown in Figure 4-6. The command specifies that the user is interested only in those alternatives for which the MAIN-OPERATING-BASE is EDWARDS. KBS responds by displaying just those alternatives in a form similar to

Command:

```
SHOW OPTIONS WITH MAIN-OPERATING-BASE EQ EDWARDS;
```

Response:

```
OPTION2 = AIR-SHOW-OF-FORCE
             FORWARD-OPERATING-BASE = TRAVIS
             BORDER                 = MATHER
             MAIN-OPERATING-BASE    = EDWARDS
             AIRCRAFT-TYPE          = A-10A
             SORTIES-PER-DAY        = 25
             TOTAL-NUMBER-OF-PLANES = 13
             NO-OVERFLIGHT-AREAS    = list
         consisting of NEVADA  and NEW-MEXICO
OPTION1 = AIR-SHOW-OF-FORCE
             FORWARD-OPERATING-BASE = TRAVIS
             BORDER                 = MATHER
             MAIN-OPERATING-BASE    = EDWARDS
             AIRCRAFT-TYPE          = A-10A
             SORTIES-PER-DAY        = 25
             TOTAL-NUMBER-OF-PLANES = 13
             NO-OVERFLIGHT-AREAS    = list
         consisting of NEVADA  and NEW-MEXICO
```

FIGURE 4-6
SELECTIVE DISPLAY OF PLAN OPTIONS

the outline display of Figure 4-1, but using only an abbreviated description.

Using these facilities of KBS, the operator may review the relationships of the various plan alternatives developed by KBS at any level of detail desired.

4.5 Displaying Reasons for Choices

We have seen that KBS builds up a plan by means of a series of choices. Either KBS or the operator may make these choices. The operator will often want to know the reasons for choices; accordingly, KBS provides a means for displaying this information. Figure 4-7 gives a number of examples of the use of this feature in several plan steps. The plan steps are those displayed in Figure 4-1.

In the plan from which the examples of Figure 4-7 were taken, the operator specified the sorties per day and specified the aircraft type as just "A-10". KBS refined this to A-10A on its own. In the absence of any other grounds for choice, it simply took the first one in a list of varieties of A-10s. If rules for selection of aircraft types were provided later, they would be used in similar situations. The reasons for MAIN-OPERATING-BASE in the AIR-SHOW-OF-FORCE plan step and for SOURCE in the OBTAIN plan step are constructed by KBS from the internal structures cf the rules themselves. These reasons are presented as they were generated except for improvements in indentation.

Many of these rules use the geographic database, which is able to find the items of a given kind which are nearest to a given location. In the case of the MAIN-OPERATING-BASE, the expert used is that described in Section 3.4.2. The items sought are airbases, and the center location is the FORWARD-OPERATING-BASE. These airbases are further ordered by a complex function which depends upon the distances of the candidate airbase from the FORWARD-OPERATING-BASE and

```
In the AIR-SHOW-OF-FORCE plan step:

WHY AIRCRAFT-TYPE;
Next in list of instances.

WHY SORTIES-PER-DAY;
You supplied the value.

WHY MAIN-OPERATING-BASE;
the AIRBASE
   which is nearest to the FORWARD-OPERATING-BASE, TRAVIS
   which minimizes  cost estimated by
      distance between which   and
                          the FORWARD-OPERATING-BASE, TRAVIS
    and
      distance between which   and
                          the BORDER, MATHER

In the OBTAIN plan step (DEPLOY phase):

WHY SOURCE;
the AIRBASE supplier
          for the MATERIEL   , group of 13 of A-10A  's
          which is nearest to the LOCATION   , EDWARDS

In the REDEPLOY plan step (RESTORE phase):

WHY DESTINATION;
Use the ORIGIN   , ELLINGTON
```

FIGURE 4-7
DISPLAYS OF REASONS FOR CHOICES

the BORDER. In the case of the SOURCE, the items sought are again airbases, but this time those which are capable of supplying the MATERIEL. KBS has an index that permits it to do this efficiently.

4.6 Display of Commentary

As KBS builds a plan, it continually checks to be sure that the plan satisfies all of the constraints which it has been given, to the current depth of expansion. In addition to determining whether or not the constraints are satisfied, KBS also tries to determine the kind and degree of error, or margin of safety, for each item involved. KBS records all this information as commentary on the choice and can use this information to direct its searches. It can also display it on demand. An example of this display can be seen in Figure 4-8.

This example shows a total of 13 comments on the choice of China Lake as the Main Operating Base in an Air Show of Force. Most of these are favorable; only five problems have been found. These are grouped into two basic failures: the lack of adequate communication gear (comments 1 through 3) and lack of high-precision navigation aids (comments 10 and 11). KBS has already been instructed by the operator to ignore the problem posed by lack of navigation aids. However, the other problems remain.

4.7 Correction of Deficiencies in a Plan

KBS frequently considers options which have problems. This is detected as negative commentary. Using the information in these comments, KBS may be able to find a means for correcting the difficulty. Such corrections are described by rules very similar to those it uses to expand plan steps. If KBS is able to find such corrections, it will add them to the developing plan structure as support plan steps. We can see the results of this in Figure 4-9. This shows one of the plan steps which KBS is working on to correct the comments shown as

```
-1        **** Bad  there is not adequate communications
                      facilities at CHINA-LAKE
                    C-W is not AVAILABLE
-2        **** Bad  there is not adequate communications
                      facilities at CHINA-LAKE
                    CABLE is not AVAILABLE
-3        **** Bad  there is not adequate communications
                      facilities at CHINA-LAKE
                    TELEGRAPH is not AVAILABLE
-4  Acceptable      low-pressure oxygen is available
                      at CHINA-LAKE
                    LOW-OXYGEN is AVAILABLE
-5  Acceptable      low-precision navaids is available
                      at CHINA-LAKE
                    A-G is AVAILABLE
-6  Acceptable      low-precision navaids is available
                      at CHINA-LAKE
                    RBN is AVAILABLE
-7  Acceptable      low-precision navaids is available
                      at CHINA-LAKE
                    TACAN is AVAILABLE
-8  Acceptable      low-precision navaids is available
                      at CHINA-LAKE
                    APP-CONT is AVAILABLE
-9  Acceptable      low-precision navaids is available
                      at CHINA-LAKE
                    TWR is AVAILABLE
-10 ---Ignored      high-precision navaids is not
                      available at CHINA-LAKE
                    ILS is not AVAILABLE
-11 ---Ignored      high-precision navaids is not
                      available at CHINA-LAKE
                    GCA is not AVAILABLE
-12 Acceptable      CHINA-LAKE is sufficiently far from
                      border, MATHER
                    could be safely decreased by 43.37295
                      along a bearing of 136.0344
-13 Acceptable      there is adequate maintenance
                      at CHINA-LAKE
                    MAINTENANCE is one of FIELD,
                       ORGANIZATION
```

FIGURE 4-8
SAMPLE COMMENTARY

```
Support
   HOW = OBTAIN
         LOCATION = Ok  CHINA-LAKE
         MATERIEL =     C-W
         SOURCE   = Ok  HOUSTON
      Expansion
         PROCURE = OBTAIN
               MATERIEL =     C-W-KIT
               LOCATION = Ok  CHINA-LAKE
               SOURCE   = Ok  HOUSTON
            Expansion
               HOW = MOVE
                     CARGO       =     C-W-KIT
                     ORIGIN      = Ok  HOUSTON
                     DESTINATION = Ok  CHINA-LAKE
                     CARRIER     = Ok  C-130E
                  Expansion
                     PICKUP   = ONLOAD
                           CARGO    =     C-W-KIT
                           CARRIER  = Ok  C-130E
                           LOCATION = Ok  HOUSTON
                     CARRY    = FLY
                           VEHICLE               = Ok  C-130E
                           ORIGIN                = Ok  HOUSTON
                           DESTINATION           = Ok  CHINA-LAKE
                           NO-OVERFLIGHT-AREAS =       list
                        consisting of NEVADA  and NEW-MEXICO
                           ROUTE                 = Ok  list
                        consisting of (29.96667,-95.33333) and
                        (31.34,-109.048) and (35.68333,-117.6833)
                     DELIVER = OFFLOAD
                           CARGO    =     C-W-KIT
                           CARRIER  = Ok  C-130E
                           LOCATION = Ok  CHINA-LAKE
         SETUP    = INSTALL
               FACILITY =     C-W-KIT
```

FIGURE 4-9
PROPOSED CORRECTION

1 - 3 in Figure 4-8, specifically the lack of C-W equipment at CHINA-LAKE. One KBS rule states that such deficiencies may be corrected by OBTAINing the missing equipment at the deficient base. In the example, KBS has found a C-W kit at Houston and has selected a C-130E to transport it to China Lake.

4.8 <u>Query Capability</u>

KBS offers the ability to retrieve information directly from its internal data base. The operator simply types a SHOW command containing an expression representing the information which he wishes to obtain. This use of the SHOW command is shown in Figure 4-10. First, KBS is asked to calculate the distance between two points and then to find the values of landing runs and runway lengths. All these commands are typed while KBS is operating on the plan shown in Figure 4-1. Thus "MAIN-OPERATING-BASE" refers to EDWARDS and "FORWARD-OPERATING-BASE" refers to TRAVIS. Finally, a new name, "BASE", is defined to refer permanently to MATHER. It is seen that this name does, indeed, have the meaning defined for it and can be used in subsequent queries. The distance from BASE to EDWARDS is the same as the distance from MATHER to EDWARDS since MATHER and BASE are now the same.

4.9 <u>Geographic Map Display</u>

The system can display a map showing the geographic setting of any plan including all sites mentioned in the plan along with any others desired by the operator. KBS automatically assembles the latitude and longitude of the desired points and of the boundaries of the desired areas, selects a suitable center and scale, transforms the latitude and longitude to map coordinates, and assigns key characters for identifying lines. Unfortunately a graphics device was not available; therefore, KBS must print characters to the terminal to make a crude map. Figure 4-11 is an example of this kind of map.

```
SHOW DISTANCE FROM EDWARDS TO MATHER;
 The value is: 273.7347
SHOW LANDING-RUN OF A-10A;
 The value is: 1260
SHOW LENGTH OF RUNWAYS OF EDWARDS;
 The value is: 15000
SHOW DISTANCE FROM MAIN-OPERATING-BASE TO TRAVIS;
 The value is: 280.088
SHOW DISTANCE FROM FORWARD-OPERATING-BASE TO EDWARDS;
 The value is: 280.088
DEFINE BASE TO MATHER;
SHOW BASE;
 The value is: MATHER
SHOW DISTANCE FROM BASE TO EDWARDS;
 The value is: 273.7347
```

FIGURE 4-10
QUERY FACILITY

```
             ********
             *      *
          @MATHER   *
          @TRAVIS   *
               **  *     ########
                 * *     #|     #
             @EDWARDS  --+--    #
                   ++++  #|     #
                       +++#     #
                          ########++++++++++
                                            @ELLINGTON


|<--                 2257.257 nm                    -->|
#   - NEW-MEXICO
*   - NEVADA
+   - ROUTE, choice 18
```

FIGURE 4-11
SAMPLE MAP

It shows the locations of interest in the plan shown in Figure 4-1. The items displayed include the various airbases, the NO-OVERFLIGHT-AREAS (NEVADA and NEW-MEXICO), and the route to be taken by the aircraft between ELLINGTON and EDWARDS. Note that this route and the boundaries of the states are identified in the key at the bottom of the map. Obviously the quality, information, and detail would be much improved by true graphics presentation.

5.0 CONCLUSIONS AND RECOMMENDATIONS

KBS has demonstrated that the techniques of Artificial Intelligence show substantial promise for the solution of military planning problems. It has done this by applying the powerful techniques of hierarchical planning and FRAME knowledge structures to an Air Show of Force action using a subset of the related military databases. KBS will either generate a plan and alternatives or allow the operator to enter his plan interactively for checking. The system will select aircraft, airbases and deployment routes using rules and constraints provided by planning strategists; however, the operator may override any constraint or choice and may enter specific choices. Explanations are available for all choices made. When there are plan deficiencies, the system will correct them if possible. KBS is prompt and provides a tolerable interactive interface to the user. The heuristic rules and deficiency correction techniques were obtained from military strategists and reflect procedures that would be followed in actual situations. Since KBS has the structure for expansion to more operationally realistic situations, it can be modified to fit many military or crisis planning problems.

5.1 KBS Advantages

KBS has the following advantages in a crisis action planning situation:

- Thoroughness: The system will always consider all factors defined as relevant. To the depth it is requested to work, it will not overlook anything because of haste, pressure, or inexperience; and it will re-examine all factors when the situation changes.

- Expertise: The system can be supplied with rules-of-thumb and criteria at all levels of detail. These can be distilled from the collective experience of a panel of expert planners and refined over a series of sessions of demonstration and evaluation. Thus the system becomes trained and can apply this expertise independently of its teachers. In other problem areas (such a medical diagnosis and the determination of chemical structures), such rule based systems have performed as well as their training panel and sometimes better than any member of it.

- Promptness: The system will produce feasible alternatives in a much shorter time than human planners. This is possible because of the incorporation of human logic and "rules-of-thumb" into the power of high speed computer systems.

- Duplicatability: Once developed and trained, such a program can be duplicated and disseminated to a large number of sites. Thus its expertise will be made more widely available.

- Consistency: The system will make the same recommendations in the same situation every time (unless some of the rules have been changed). It will not respond to stress, fatigue or boredom. Also different copies of the system will act alike.

- Privacy: Because of the encoded knowledge of many military experts, detailed contingency plans can be made with a minimum of exposure. Personnel outside the immediate planning group need not be involved.

- Adaptability: The planning procedure can be controlled and molded by the planning officer to consider political situations and the operator's personal preference.

- Education: Use of the system by inexperienced planners will teach them the expertise of previous planners.

Expert planning systems offer the opportunity to capture the expertise of experienced officers and to make it available to commanders at widely dispersed sites at any time.

5.2 Remaining KBS Risk Areas

KBS has not yet demonstrated that such a system can be implemented in an operational environment. The following risk areas remain:

- Operational Databases: Operational databases are large and organized in a manner unsuited to Expert Systems. Dealing with such large amounts of data in an efficient and timely manner is a difficult problem not unique to KBS. Abstractions of the databases may be necessary in order to facilitate access to the appropriate data. In addition, efficient conversion of the data will be necessary. Once the planning situation is known, it is anticipated that most of the relevant data will be accessed and converted in an initial access to the military databases.

- Expanded Situations and Detail: As the number of possible situations is increased and the detail of the possible plans expands, the sheer magnitude of the needed experts and constraints becomes formidable. The way to deal with such large planning systems seems clear through hierarchical plans and layered control structures; however, it has not yet been done.

- Use and Development of Subplans: Currently KBS redevelops similar or identical subplans for each option it considers. In an operational environment it is unlikely that this inefficiency can be tolerated. Some preliminary work has been done in the use of pre-stored and similar subplans, but it needs completion.

- Implementation Language and Base Hardware: The current implementation of KBS is in INTERLISP. INTERLISP is specially designed for Artificial Intelligence and is a powerful research and development tool It does not, however, produce particularly efficient operational systems. Furthermore, it is not a standard DoD software language. Unfortunately the development of expert systems in these standard languages is extremely difficult; reimplementing an existing expert system in ADA is possible, but it would be tedious and expensive. An alternative is a special computer designed to execute INTERLISP systems. In this case, an interface to the military networks would be required for database access.

- Performance: This is affected by all of the other risk areas. If a dedicated computer system is used, the most likely remaining performance risk will be the time required to make initial access to the military databases.

In addition to the above risk areas, a number of KBS areas need to be completed. These are not areas of particular risk but in some cases do involve substantial effort. The incomplete areas that need further development are:

- User Interface: This area must be improved dramatically before user acceptance will be obtained. A graphics capability is required for the operator to be able to observe and control the planning process. Graphics would provide visual clarity to the various options within the plans through the display of maps, trees, time lines, etc. A more helpful interaction and a more forgiving command language are also required.

- Use of Commentary: Currently the system makes only limited use of the commentary provided by the constraints. More sophisticated control rules need to be added so this information can be used better to guide the exploration and evaluation of alternatives.

- Entry of Experts and Constraints: To expand KBS and keep it current, the addition of new rules and projects will have to be simplified.

5.3 Recommendations

To demonstrate the utility of KBS and similar systems in the military planning environment, it will be necessary to involve these systems in actual military planning situations. Reduced scale databases and situations will improve the theoretical foundations of Artificial Intelligence Planning Systems; however, it is impossible to convince users of military planning systems that any new system is valuable without actual involvement of the system in realistic situations. For these reasons, it is recommended that KBS be developed to the point that it can be used in a military planning exercise. This prototype version could then be used parallel to, and compared with, existing systems in a military exercise. To provide for quick development and minimum interference with existing systems, the system should be developed on a dedicated computer with strong graphics support. This development system would be interfaced to the military networks to provide it with access to the required data.

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