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Knowledge Based Mechanisms for Plan Generation

NASA Contract No. NAS 9-19117
Mid-Term Report

Knowledge Based Systems, Inc.
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College Station, TX 77840

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1 Executive Summary

1.1 Introduction

The goal of this Small Business Innovation Research project is to investigate, design and develop technology to support the planning and execution of multiple flights in the NASA mission planning domain. This report documents the progress and results achieved during the first year of the project and details the future direction of our work.

1.2 Organization of the Report

An overview of our approach to NASA mission planning is presented in Section 2. Section 3 summarizes the project progress to date. The requirements of the proposed Knowledge Aided Mission Planning System (KAMPS) are described in Section 4. Section 5 summarizes the information that is managed by KAMPS. Section 6 discusses the change impact analysis capabilities provided by KAMPS. Section 7 discusses the software design of KAMPS. Finally, in Section 8, we discuss the work that needs to accomplished in the remaining project period.

2 Overview of Our Approach

Our approach to designing and building KAMPS is summarized in the following sections.

2.1 Perform Knowledge Engineering

We interviewed several NASA and RSOC personnel in order to understand the space shuttle flight design process. The knowledge engineering results were used to characterize the ontology of the domain. The domain analysis involved identifying the activities and events that occur in flight design and artifacts that get delivered during the flight design life cycle. This task helped enhance our understanding of the various mechanisms involved in the flight design process. Conceptualizing the inter-relationships among products, meetings and activities, and the resource contention between them, helped identify the planning requirements for KAMPS.

2.2 Define Kamps Requirements

Based on the results of Task 1, we developed the initial requirements for KAMPS. We refined the first cut requirements based on discussions with NASA. Section 4 describes the KAMPS requirements.

2.3 Perform Kamps Information Modeling

Information modeling of the flight design process enabled us to identify the information components and to understand the relationships between the various information components. We also used this to develop the database model for KAMPS.

2.4 Design Change Impact Prediction Mechanisms

One of the primary requirements of KAMPS is to predict (in real time) the impact of delays and other kinds of changes that could potentially occur during the flight design process. We designed qualitative and quantitative reasoning mechanisms that will offer this support.

2.5 Develop Framework for Acquiring and Maintaining Flight Design Process Knowledge

Our initial knowledge engineering revealed that there are many aspects of the flight design process that are generic. Although each flight is custom made and has many unique features, we observed that there is a significant amount of information that is common among them. This observation led to the development of the concept of *templates*. Templates are classes of flights. Instead of starting from scratch every time a flight is to be planned, a user can select an appropriate template from the repository and adopt it to the specific flight by making appropriate changes.

2.6 Design KAMPS Software

This task involved designing the architecture for KAMPS and arriving at a detailed breakdown of the class structure of the various architectural modules.

2.7 Develop Level 1 Planning and Resource Allocation Algorithms

Level 1 KAMPS takes cognizance of resource constraints while performing planning and change impact prediction. We modified several existing algorithms for scheduling, allocating resources, and leveling resources to satisfy specific NASA requirements.

3. Summary of Progress

The following Phase II objectives have been achieved to date:

1. We have established the requirements for KAMPS. The requirements were developed through a careful analysis of the NASA flight design process. The data on the flight design process was gathered through discussions with NASA and RSOC personnel and from several documents supplied by NASA. We performed process modeling and information modeling of the mission planning process, and this helped us identify the functional requirements of KAMPS. A large part of the initial effort was in understanding and identifying the processes and the ontology of the mission planning domain.

2. We have developed a software design for KAMPS, which is still in the process of iterative refinement. KAMPS supports multiple users and is based on a client server architecture.

3. We designed new algorithms and adapted existing algorithms for supporting the scheduling and resource allocation strategies. These algorithms allow the KAMPS user to generate schedules and allocate the resources.

4. We evaluated various Commercial Off The Shelf (COTS) tools for integration with KAMPS. KAMPS will be integrated with spreadsheet and project planning COTS tools.

5. We have started the prototype development for KAMPS. We completed the implementation of the template maintenance and template update capabilities of KAMPS.

4 KAMPS Requirements

The KAMPS requirements were developed based on data gathered from knowledge engineering of the NASA mission planning domain. KAMPS is being developed at two levels: Level Ø KAMPS provides for flight/template creation, maintenance, and dynamic update. Level 1 KAMPS contains resource information and provides for dynamic and real time scheduling and resource allocation. The following sections describe the KAMPS requirements in greater detail.

4.1 Functional Requirements

A large part of the effort during the first year of the project was spent in identifying and refining the functional requirements for KAMPS. The Level Ø functional requirements for KAMPS have been finalized. Level 1 functional requirements have also been identified and are under refinement. We expect the KAMPS functionalities to be further refined based on the feedback obtained as a result of the evaluation of the prototype by NASA. The following sections summarize the Level Ø and Level 1 functional requirements.

4.1.1 Level Ø Functional Requirements

The KAMPS Level Ø functional requirements are:

1. KAMPS should provide a means for creating and maintaining flight templates.

A flight template contains mission design process information that is fairly common to different flights. KAMPS will offer users the capability to create and maintain flight templates. Flight templates should contain common information about flights in terms of the products and activities in the flights and the relationships between them at multiple levels of abstraction.

2. KAMPS should provide a means for creating and maintaining flights.

KAMPS should provide for tailoring a generic flight template to the specifications of a particular flight based on the flight requirements. This involves modifying, adding, and deleting the activities, products, and events in the flight design process and the relationships that exist between them.

3. KAMPS should provide a means to capture and display flight information from product centered, activity centered, and event centered views.

One of the innovative approaches we are adopting in KAMPS is to differentiate the information maintained in KAMPS into three views: product centered, activity centered, and event centered. The product centered view is concerned with the products, their components, where they are used, and other relationships between them. The activity centered view is concerned with the various tasks that need to be performed to realize the products. This view is concerned with tasks, sub-tasks, precedence relations, etc. Finally, the event centered view is concerned with capture, maintenance, and display of information regarding the significant events and milestones that occur during the flight design process. Based on their roles, different users might be interested in different views of the flight design process, and KAMPS should support easy transition from one view to another. KAMPS should also allow for input to the system through the product centered, activity centered, and event centered views in both graphical and textual format.

4. KAMPS should provide a means for updating flight information as the flight design process progresses.

KAMPS users should be able to update flight information as the flight design process progresses.

5. KAMPS should provide the capability for change-impact analysis with respect to any changes in the flight design or activity delays.

KAMPS should offer the capability to dynamically change the activities, products, and events of a particular flight and find the impact of these changes on the design and progress of the project. Change impact analysis is an important functionality provided by KAMPS. We have segmented this functionality into two types:

1. Delays in meetings and scheduled product/component deliveries

KAMPS users will be able to determine the first order (immediate) and higher order (longer term) impacts due to the delay in a particular milestone, meeting or activity. For this functionality, KAMPS will rely on the precedence relationships between activities and other relationships we have identified in the flight design process (these relationships are discussed in greater detail in Section 4). In Level Ø, the delay impact analysis is done assuming unconstrained resources.

2. Changes in the process or value of products

Changes in the value of a product affects the way activities are performed in succeeding products. For example, the output of ONOR03 (sequence of events) determines the number of scenarios considered in DSCT01. Similarly, the specific process used to produce a product can have a bearing on the processes used to produce downstream products. KAMPS will also provide the capability to determine the impact of changes in the value or process of a product. This type of information is very important because of potentially significant effects on most subsequent activities. KAMPS provides for the capture of and reasoning with such kinds of knowledge. In Level Ø, this impact analysis will be performed at a qualitative level, where as Level 1 will quantify the nature of these impacts in greater detail.

4.1.2 Level 1 Functional Requirements

The Level 1 KAMPS enhances the change impact analysis functionalities of Level Ø by taking into account the resource information available across multiple flights. Effects of delay in activities/meetings or other events are propagated by dynamically calculating new schedules based on the resource availability across the multiple flights.

4.2 KAMPS Representational Requirements

Level Ø KAMPS must provide for the representation of three kinds of information relevant to the flight design process: 1) the products that are delivered, 2) the activities and meetings that are involved in delivering the products, and 3) the events/milestones that occur during the flight design process. Moreover, the information about flights needs to be represented at arbitrary levels of detail.

4.2.1 Product Centered Representation

KAMPS should allow the user to represent the network of products and their interrelationships in the flight design process. In this representational scheme, a product is an artifact delivered during the flight design process such as ONORA03. Products in the mission planning domain are usually data elements, trajectories, dates, sequences of events, or any combination of these. Conceptually, a meeting can also considered to be a product, which could be a document generated from the meeting, or something intangible as a consensus or approval that emerges from the meeting activity. Using this representation, KAMPS should capture, display, and reason with the product, their attributes, and the various interrelationships. The KAMPS product-centered scheme should allow for:

1. adding and deleting products,

2. changing the attributes of a product (such as processes, inputs, outputs, etc.),

3. adding/changing the product-product, and product-activity relationships, and

4. maintaining information about the different output ranges the product can take and the effect of these different output values on the related product processes.

4.2.2 Event Centered Representation

KAMPS should permit the project to be represented as a sequence of chronologically ordered events along the Launch Minus Date timeline. The events are product delivery milestones, product initiating event, meeting start or end times, etc. In the event centered view, the functionalities provided by KAMPS include:

1. add delete events,

2. add/delete/change the attributes of events, and

3. change chronological relationships between events.

4.2.3 Activity Centered Representation

The planner must be able to represent a project as a network of activities. An activity is a collection of tasks that are performed to produce a product. Similarly, in the case of a meeting, we can individuate the activities that constitute the meeting. Thus, an activity can be classified as either a product producing activity or a meeting activity. KAMPS should be able to represent all relevant information about the activities in a flight design.

In the activity centered view, the functionalities provided by KAMPS include:

1. add delete activities from the template,

2. change the attributes of the activity, and

3. add/delete/change relationships between activities.

4.2.4 Template Building and Maintenance

KAMPS will have in its database generic project information templates. KAMPS should provide facilities for editing and changing the generic template and instantiating the template for specific flights.

4.3 Database and Access Control Requirements

The KAMPS database should provide distributed support, offering concurrent access to multiple users for template/flight creation and maintenance. KAMPS users could perform impact analysis at different locations, running different modules of the application. Because KAMPS supports multiple users with different user roles, it should also provide for controlling the access provided to these users. KAMPS should permit the capture of various user roles and the extent of access that is provided to each role. We have identified four user roles:

1. System Administration: System administrators should have access to system level changes, such as setting access levels for different users, setting passwords, adding and deleting users to the system, etc.

2. Template Maintenance: This user role should provide access for creating new templates, maintaining and updating existing templates, etc.

3. Flight Maintenance: Users with this role should have access to change the status and information associated with current flights. They update the actual progress of the flight vis-a-vis the plan and monitor the effect of any deviations.

4. Impact Analysis: This user role provides access to perform impact analysis, such as finding the effect of changes and delays in products. Impact analysis has the loosest of user restrictions: all users can perform impact analysis because all information in impact analysis will be managed in read-only mode. Thus, for example, users can't update the flight schedules from impact analysis mode.

5 KAMPS Information Models

As a part of the Phase II effort, we performed information analysis of the mission planning domain. This information modeling effort helped us 1) identify the information

components that are collected, stored, and managed during the flight design process, 2) identify the rules governing the management of this information, 3) understand the ontology in the mission planning domain, and 4) develop the database design for the KAMPS software.

SMARTER™, KBSI's information modeling tool (based on the Air Force IDEF 1/1X methods) was used for the information analysis. The knowledge gained in performing the information analysis exercise gave us valuable insight into the flight design process, and in particular, the planning requirements for the KAMPS. In the following sections, we explain a few key information components, their attributes and a few concepts relevant to these components.

5.1 Flights

Flights are the focus objects of KAMPS. The essential attributes of a flight are the cycles involved in the flight, the complexity factor for the flight, its launch date, and other attributes like the existence of a payload, the experiments that are to be performed in orbit, the launch sites, etc.

5.2 Templates

Templates are flight classes that the user can use to create specific flights. Flights are created by instantiating a particular template by tailoring it with the specifics of a flight. Templates contain the commonly occurring products, activities and their relationships. Thus, conceptually, templates capture and store the information common to different flights.

5.3 Products

Products are distinguishable and functionally or parametrically coherent artifacts that are produced during the flight design process. Products could be data (represented in the form of charts, vectors, summaries, budgets, etc.), verification statements, sequences of events, landing opportunities, etc. Products could be defined at various levels of detail. Products decompose into sub-products (or components), and sub-products could decompose further into sub-sub-products, and so on. For example, ONOR03, DSCT01, RNDZ05 are higher level product in the flight design process. Examples of artifacts at the next level of detail (for ONOR13) are: 1) Pre-Deorbit and Day 1 state vectors, 2) nominal EOM Landing-100

deploy and no-deploy vectors, and 3) Worst case CONUS landing. Thus, KAMPS provides for modeling products at multiple levels of abstraction.

A few examples of attributes that characterize a particular product are: 1) dynamic and static inputs (e.g., the dynamic inputs to ONOR13 are ASCT06 and ONOR09), 2) functionality (e.g., one functionality provided by ONOR13 is it is used in DSCT01 to compute the worst case Deorbit delta V's), 3) cycles in which the product is delivered (e.g., ONOR13 is delivered in AFP, CFP, ENG, FLT, and FRR cycles), and 3) the output type: a one dimensional vector, or a multi-dimensional vector, a set of data points, a simple verification statement, a combination of landing sites, an instance of time such as MET (mission elapsed time), etc.

5.4 Activities and Processes

Activities are the tasks performed that contribute to the realization of a product. Each product is associated with one or more activities. Activities capture the information necessary to perform flight scheduling, resource allocations, and impact analysis. Just as with products, activities can have multiple levels of abstraction. A few examples of attributes characterizing activities are: 1) the product with which the activity is associated, 2) duration of the activity, 3) the cycle in which the activity occurs, and 4) the resource requirements for the activity.

The ordered sequence of activities associated with a product is referred to as a process. The same product can possibly be produced through performing a different set of actions in a different sequence. Thus, a product can have alternate processes. But for a particular flight, at a particular instance, there is always a preferred way of performing the product (that is, a preferred process).

5.5 Relationships

In this section, we briefly describe a few common relationships occurring between the information components described above.

5.5.1 Activity Relationships

Temporal relationships

KAMPS will support the existence of different types of temporal relations between the activities, such as finish-to-start (Activity A2 can't start until Activity A1 is finished), start-to-start, start-to-finish, and finish-to-finish relations.

5.5.2 Product-Product Relationships

Input-Output

We say a product P1 is an input to a product P2 if some or all the outputs of P1 are used in the production of P2. Because the output of one product is required to produce the other product, the input-output relation implies the existence of a precedence restriction among the corresponding associated activities.

Lag

In order to account for the phenomenon from the previous case, we introduce an attribute 'Lag' to an input relation. If P_1 is required for the production of P_2, but P_2 can start and run for some amount of time t before it actually requires P_1, then the lag attribute of the input relation between P_1 and P_2 is t. Representing and reasoning with this kind of knowledge is crucial to generate reasonably accurate predictions of the impact of delays.

Value-affects-Process

In the context of impact analysis, process change indicates a change in the manner that activities are performed in a product. It could be addition or deletion of certain tasks, changes in the sequence in which the tasks are performed or the use of a completely different set of tasks. Sometimes the process of a product could be affected by the value of one or more of the input products. That is, if the value of the input product is in one range, a set of tasks is performed in the succeeding product, but if the value of the input product is in a different range, a different set of activities is performed in the succeeding product. For example, the output of ONOR03 (sequence of events) determines the number of scenarios considered in DSCT01. In such cases, we say that there is a value-affects-process relation between the two products. In KAMPS, this knowledge will be explicitly captured and used to perform impact analysis, and to incrementally refine the plan as more information is acquired about a flight.

Substitute-of

The substitute relationship holds between a three tuple: <input product, output product, substitute product>. *Input product* and *output product* refer to products that have a input-output relation existing between them. However, in some cases, if the input product is not available on time, a substitute product could be used instead. A substitute for a particular product is usually an estimate, an approximation, or a previously available product or a functionally similar product. A few examples are:

1. Sequential Mass Properties from PROP02 is an input to DSCT06, but if sequential mass properties are unavailable, FOP presentation charts from PROP01 may be used as an alternative.

2. If pre-CIR work in DSCT08, and if DSCT01 is not created in AFP and CFP cycles, then the deorbit Apogee from lvlaflt.fcf is used.

6 KAMPS Change Impact Analysis

At Level Ø, KAMPS provide mechanisms for high level qualitative reasoning that support the planning of the flight design process. Change impact prediction capability is a critical qualitative reasoning aid. In this section, we briefly discuss two impact analysis modes provided by KAMPS 1) delay impact analysis and 2) process analysis. At Level 1, KAMPS integrates the scheduling and resource allocation strategies into the impact analysis mechanisms.

6.1 Delay Impact Analysis

An important change impact analysis capability provided by KAMPS is predicting the effect of a delay in completing a particular product or component. Users may be interested in identifying the products that are affected by the delay and the exact nature of the impact. The effect of delays are propagated through the input-output relationships. During impact analysis, the KAMPS impact analyzer will account for the presence of substitutable products and products that can be started even if they do not have all the inputs. This functionality is provided in KAMPS through the introduction of *substitute-of* relationship and an attribute *lag* that qualifies the input relationship. KAMPS will provide for automatic delay impact analysis that is based on well defined semantics of these relationships and a knowledge-based reasoner that propagates the impacts through the network of these relationships.

In this mode of change impact analysis, KAMPS provides the impact of delay in an activity, product delivery, or event in the project. Examples of questions that the KAMPS impact prediction module will answer are:

1. If activity A is delayed, what are the 1) immediate impacts (first order) and 2) long term impacts (higher order) on downstream activities?

2. If event A is delayed, what are the 1) immediate impacts (first order) and 2) long term impacts (higher order) on the downstream events?

3. If product A is delayed, what are the 1) immediate impacts (first order) and 2) long term impacts (higher order) on the downstream products?

Other requirements of the KAMPS change impact prediction module include:

1. KAMPS should provide mechanisms to reason and present different kinds of impacts as illustrated from the preceding paragraph. KAMPS should also capture and present textual information about the major impacts of a delay.

2. KAMPS must provide graphical and visual support for convenient communication of the impact analysis. For example, the orbit products affected by DSCT01 can be shown by 1) highlighting the impacted products using a color scheme, 2) listing the affected products in a list box and 3) giving a textual summary of the impact, etc. It should be possible to perform impact analysis by moving the icons representing milestones along the timeline and observing the effect this has on other events and milestones. Further, the display should facilitate viewing specific sets of events (e.g., the delivery dates of the Orbit products) on different launch-minus time scales and different cycles.

6.2 Process Impact Analysis

If Product P1 is used in Product P2, sometimes the activities performed in P2 are affected by the output of P1. That is, the *value* of P1 affects the *process* of P2. For example, ONOR03 (sequence of events) affects the process of the succeeding products, such as, if the event title component of ONOR03 does not contain events such as "payload deploy," then the number of scenarios considered is fewer. In such a case, we say that there exists a value-affects-process relation between the two products. KAMPS will capture such

relationships between products, performing the necessary reasoning based on these relationships in change impact analysis.

We have already implemented a qualitative version of the process impact analysis in Level Ø KAMPS. This will be extended subsequently to quantify the exact nature of the affects. KAMPS will eventually have delay impact analysis both at the template and flight level. We are targeting to complete the initial prototype of KAMPS by early May, with the final version planned for August.

6.3 Scheduling and Resource Allocation Strategies

Resource allocation and scheduling strategies for KAMPS are based on heuristic approaches. Various resource allocation strategies will be made available, and the KAMPS user can select from a variety of priority rules to allocate resources. Resources are allocated, and low cost schedules are generated based upon the selected strategies. The scheduler will permit the KAMPS user to rapidly compare alternative scenarios. For Level 1, the scheduling and resource allocation methods will be integrated into the impact analysis functions for more comprehensive change impact prediction.

7 KAMPS Software Design

During the period, we developed the detailed software design for KAMPS. The software design of KAMPS takes cognizance of the requirements of a distributed system implemented in a client server architecture. A significant emphasis while designing the KAMPS software was on maintaining a strict modular structure and in delineating the client and server functions. The KAMPS software consists of the following modules:

1. The Graphical User Interface (GUI)
2. The Information Manager (IM)
3. The Reasoner
4. The KAMPS Database.

Figure 1 shows the functional KAMPS architecture.

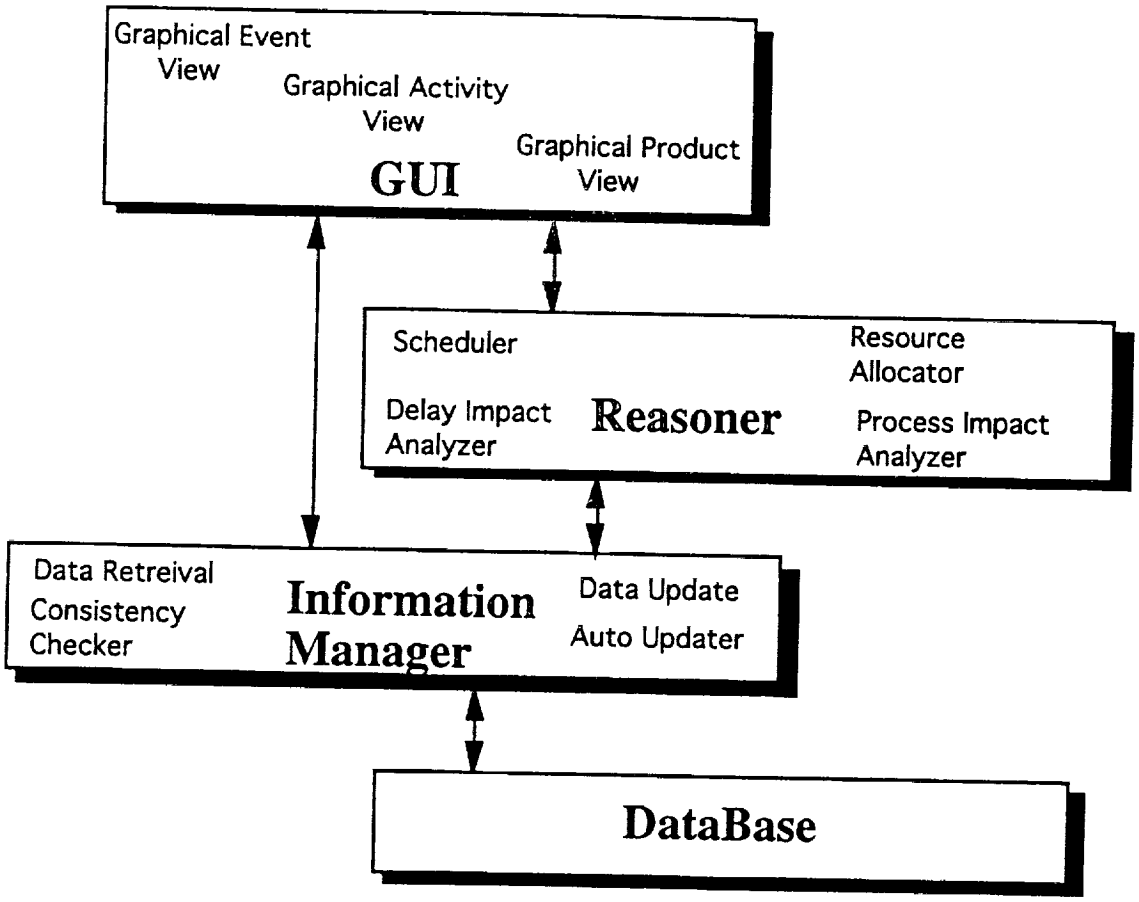

Figure 1. The KAMPS Architecture

The **Graphical User Interface (GUI)** components provide the functionality needed to satisfy the visualization and user interaction requirements. It supports menus and dialog driven interactions, as well as canvas interactions for all three representational views. We have developed and implemented most of the dialog based interactions from all three representational views. The completed GUI displays will include:

1. Hierarchical display of products in the flight design process and their interrelationships,

2. Hierarchical display of activities involved in delivering the products, and their interrelationships, and

3. Charts, timelines, and calendars of the events and the milestones along the LMD line.

The **Information Manager (IM)** module retrieves and updates the information on the project based on the user's input in any of the three representational views. The information manager also does consistency checks between the information recorded in the three **GUI** modes. The **Reasoner** module provides the functionality for change impact analysis. It contains the global functions which propagate the impact of delays and design changes. At Level 1, it also performs scheduling and resource allocation. The **Database** module forms the relational repository of the various information components that is managed by KAMPS.

We have developed the class structure for the IM module, the Reasoner module, and the GUI module. The structuring was done so as to make the overall architecture modular and extendible. This will reduce the amount of design restructuring needed to scale up from Level Ø to Level 1. The member functions for each of the classes manipulate data in the Microsoft Access® database through the ODBC server. The rationale for using ODBC is to provide portability between databases.

8 Future Work

Planned work for the project is summarized in the following sections.

Task 1 Complete Level Ø KAMPS Implementation

We will continue with the detailed implementation of the KAMPS Level Ø software. After completing Level Ø, we will demonstrate the Level Ø capabilities to NASA. We will create initial templates of the NASA flight design process, and use them as a test bed for the Level Ø prototype testing and demonstration. This phase is expected to be complete by early May 1995. The prototype KAMPS will be demonstrated at NASA. The feedback obtained from KAMPS users will be used to refine the prototype.

Task 2 Refine the KAMPS Level Ø Prototype

Based on the feedback obtained from the evaluation by the NASA domain experts, we will refine the Level Ø prototype. This process is expected to be iterative and the Level Ø prototype will evolve as a result of continuous interactions with NASA.

Task 3 Perform Initial Level 1 KAMPS Implementation

The next major phase for KAMPS will involve the implementation of the Level 1 functionalities. This task will essentially consist of implementing and integrating the

scheduling and resource allocation algorithms into the Level Ø KAMPS. This task will also involve enhancing the change impact analysis capabilities of KAMPS to incorporate the constraints imposed by the resources. This task is expected to progress until the end of July 1995.

Task 4 Complete Detailed Testing and Documentation of the Software

After incorporating the Level 1 functionalities, we will conduct a rigorous evaluation and test of the KAMPS prototype for further refinements and modifications. We will also write the KAMPS users manual. This task will also involve revisiting the requirements and the software design for further refinements and updates. This task is expected to continue until the end of the Phase II effort.

Task 5 Install Kamps and Develop a Technology Transfer Plan

By the end of Phase II project, we expect to have the final version of KAMPS installed at NASA. We will also prepare a plan to transfer KAMPS technology to other potential customers.

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13. ABSTRACT (Maximum 200 words)

This report describes the work performed in the first year of the project. The main goal of the project was to design and build a planning tool for use within the flight design area that 1) increases the quality and speed with which plans can be formulated and 2) reduces the level of effort needed to determine the impact of changes. The project tasks have progressed according to schedule. The project results to date are 1) information and process models of the flight design processes (based on knowledge engineering with flight design personnel), 2) characterized requirements of a Knowledge Aided Mission Planning System (KAMPS), 3) implementation design of KAMPS, and 4) partial implementation of KAMPS. We anticipate that a prototype version of KAMPS will be available for initial demonstration by May of this year.

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