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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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AGARD LECTURE SERIES 192

New Advances in Mission Planning and Rehearsal Systems

(Les Nouvelles Approches pour les Systèmes de Planification et de Simulation des Missions)

*The material in this publication was assembled to support a Lecture Series under the sponsorship of the Avionics Panel of AGARD and the Consultant and Exchange Programme of AGARD presented on 11th—12th October 1993 in Kjeller, Norway, 14th—15th October 1993 in Madrid, Spain and 28th—29th October 1993 at Hanscom **AFB,** Massachusetts, United States.*

NORTH ATLANTIC TREATY ORGANIZATION

Published October 1993

Distribution and Availability on Back Cover

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North **Atlantic Treaty Organization**
Organisation du Traité de l'Atlantique Nord

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- Providing scientific and technical advice and assistance to the Military Committee in the field of aerospace research and development (with particular regard to its military application);
- Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;
- Improving the co-operation among member nations in aerospace research and development;
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Published October **1993**

ISBN 92-835-0723-1

SPS

Printed by Specialised Printing Services Limited
40 Chigwell Lane, Loughton, Essex IG10 3TZ

Abstract

Modern data processing technology with greatly enhanced capabilities is being used in both the airborne and ground-based segments of the NATO Air Forces. A key element in the interface between these segments is provided by the mission planning systems which are used to analyse, fuse and refine the information at air bases. This information is used to generate the mission plans before they are loaded into the aircraft's avionics system for use during the mission. The synergy of modem avionics systems and ground-based data networks cannot be fully realized unless mission data are provided effectively and rapidly to aircraft before the mission is commenced. Aircrew workloads must be minimized, both before and during flight, by the development of user-friendly planning systems which incorporate rehearsal facilities. The report from Joint Working Group 15, “Mission Planning Systems for Tactical Aircraft”, will be used as the basis for this Lecture Series.

The aim of Lecture Series 192 is to present some of the design and engineering aspects of mission planning systems, .with particular emphasis on human factors considerations. Examples of modern mission planning and rehearsal systems will, be described.

This Lecture Series, sponsored by the Avionics Panel of AGARD, has been implemented by the Consultant and Exchange Programme.

Abrégé

Des technologies modernes de traitement de données avec des capacités améliorées sont utilisées à la fois pour l’élément navigant et pour l’élément au sol des forces aériennes de l’OTAN. Sur les bases aériennes, les systèmes de planification de la mission qui servent à analyser, à fusionner et à apurer les informations jouent un rôle clé dans l’interface entre ces diffkrents éléments.

Ces informations servent a l’klaboration des plans de mission qui sont introduites dans les systkmes avioniques des akronefs avant la mission. La synergie des systkmes avioniques modernes avec les rkseaux de transmission de données au sol ne peut être réalisée que si les données concernant la mission sont fournies au système avionique de façon précise et rapide avant le dkcollage.

La charge de travail des équipages doit être rkduite au minimum, tant avant qu’aprks le vol, par le dkveloppement de systèmes conviviaux de planification qui offrent des possibilités de répétition de la mission. Le rapport du groupe de travail commun No. 15 sur “Les systèmes de planification de la mission pour les avions tactiques” servira de base à ce cycle de confkrences.

L‘objet du cycle de conferences 192 est de présenter certains aspects de la conception et de la réalisation des systemes de planification de la mission, en particulier en ce qui concerne le facteur humain. Des exemples de systkmes modemes de planification et de répétition de la mission seront donnes.

Ce cycle de confkrences est présenté dans le cadre du programme des consultants et des kchanges, sous l’égide du Panel d’avionique de l’AGARD.

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Contents

INTRODUCTION AND OVERVIEW

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1. INTRODUCTION.

This Lecture Series aims to present a picture **of** the fundamental concepts which determine the characteristics of modem Mission Planning Systems and provide some illustrative examples of such systems. Much of the material which will be presented has been derived from the work carried out by an AGARD Working Group on Mission Planning which has been published in the form of two AGARD Advisory Reports (Refs 1 and 2).

Mission Planning is an essential pre-requisite to the successful execution of any military aircraft mission. It may be carried out in great detail in advance of the mission and include precise information about how a specific target is to be attacked, or it may be that only the outline parameters can be defined before the start of the mission because some of the details depend on information obtained during the course of the mission itself. In the case of re-active types of mission such **as** combat air patrols the latter is invariably the case, and refining of plans must be carried out during the mission. Thus planning can include both pre-flight and in-flight elements.

The execution of the mission planning **task** is profoundly affected by the extent to which the operations being planned had been forseen and pre-rehearsed. In the memoirs of Lord Carrington (Ref.3), he states that of the thirty occasions during a period of 25 years in which British forces had been engaged, only two had been forseen. Moreover, in recent years profound changes have taken place in the NATO military posture so that there appears much less probability of full-scale attack into Western Europe and, by comparison, limited conflicts in other regional areas are assuming much greater importance.

In terms of the requirements for mission planning systems, these limited regional conflicts may differ from a major European conflict in the following ways:-

In regional areas the databases which are at first available may be inadequate and need rapid upgrade.

The amount of training and rehearsal done in these regional areas may be zero or minimal

Missions in these areas may have to be of new, untested, types and may need to evolve during the conflict.

These changes became apparent during the "Desert **Storm**" operation from which some lessons will have to be learned for the evolution of future mission planning systems. Not least of these lessons may be the importance of rehearsal as an integral part of mission planning.

As shown in Table I, another way in which mission planning systems may be classified is according to their physical location. Although the most common form of system is constructed around a computer located in a building at an air base, the possibility of alternatives exists, It is certainly possible, and for in-flight planning and re-planning may be essential, that planning may be carried out on board an aircraft which is carrying out a mission. It is also possible that mission planning is carried out in another aircraft which is acting as a control centre for an operation and may be physically quite remote from the area of the mission itself. Examples of aircraft specifically intended for this airborne planning and control function are the AWACS and ABCCC.

TABLE I

Phase	Location	Operator
Pre-Flight	On the **ground**	Flight Crew or Planners
Pre-Flight	Mission Aircraft	Flight Crew
In-Flight	On the ground	Planners
In-Flight	Another Aircraft	Planners
In-Flight	Mission Aircraft	Flight Crew

Table I also shows two alternative types of operator for mission planning systems; they may be either the aircrew who will (or who are) carrying out the mission, or they may be specialist planners. The choice of who should *carry* out the pre-flight planning using a ground-based planning system is not clear-cut: this is topic which will be referred to later in this introduction and **also** in subsequent lectures.

Presented at an AGARD Lecture Series on **'New** *Advances* **in Mission** *Planning and Rehearsal Systems: October 1993.*

Amongst the factors which determine which of the altemative systems shown in Table I is actually implemented are the following:-

The type of mission (and whether it is pro-active or re-active)

The available time.

The mix of aircraft in the mission.

Data sources.

Communications (Availability and Security).

The Avionics fit in the mission aircraft.

In most cases planning is not carried out in one location only, or by any one section in a command and control organisation, and therefore certain elements of a plan may be generated in one part of the organisation, other elements in other parts and in other places. This is almost inevitable with a complex mission involving the collaborative operation of a number of different types of aircraft, perhaps together with ground forces or naval forces. With such a mission, a successful plan can only be achieved with a well-organised structure and very exactly defined boundaries of responsibility. The structure must be hierarchical so that the planning process is an integral part of the command and control function,

The existence of such a management structure is matched by a well-defined series of stages or actions which are to be carried out at the different levels in that structure. A typical flow-chart for these actions is shown in Fig.1, starting with the initial issuing of a tasking message and terminating with the production of a mission plan which is provided to the aircrew and also loaded into the avionics system of the mission aircraft. The number of stages will vary according to the particular command structure. Note particularly the concept that at every stage in the planning process there is a review of the output from that stage which may result in a decision to re-iterate through the planning process, either in that stage only or perhaps going further back through the chain to an earlier stage if some basic incompatibilities have been found. The feasibility of such re-iterations is, of course, highly dependent on the availability of adequate time. Note also that both in the preparation of plans and in their reviews, collaboration and comparison must be taking place with other parallel activities, particularly if a joint excercise is being planned which involves aircraft or other assets from other bases. Thus, an effective communications network to other bases is an essential feature of most mission planning systems.

In this Lecture Series the emphasis of the lectures will be on the final stage shown in Fig.1, the preparation of detailed plans which will generally be carried out at the squadron level, at an air base or on-board an aircraft carrier. The essential functioning of the mission planning system designed to perform this final planning function is shown in fig.2.

2. DESCRIPTION OF A GROUND-BASED MISSION PLANNING SYSTEM.

For a pre-flight planner of this type, intended to be used at the squadron level, the system is physically constructed around a fairly powerful computer. A schematic diagram of such a mission planner is shown in Fig.3, which shows an arrangement which is essentially the same as that of many other computer-based data processing systems. Fig.4 shows the practical implementation of a modem ground-based mission planning system.

The early computer-based mission planning systems did not generally use general purpose, commercially-available computers because mission planning requires both hardware and software features which were not, at that time, available on such machines. Principal amongst these is the need to process, store, display and print highly detailed maps, and for these and other reasons both the hardware and software used were generally specifically developed for the mission planning task. These systems then had significant disadvantages as they were:

Application specific
Proprietary
Inflexible
Expensive to develop and to maintain

Recent developments in commercial workstations have significantly improved their capabilities in the critical areas, and modem mission planning systems are increasingly being implemented by using workstation software and hardware which has been developed for the commercial market and is thus widely available at a significantly lower cost of ownership than hardware and software developed specifically for the mission planning application.

Inputs can be made to the system both manually and by direct feed from networks which, as already described, couple the mission planning system to other systems. Using such networks the mission planning system will have access to a range of up-to-date data such as intelligence, weather, plans, friendly and enemy assets, etc. In addition the system will contain, or have access to, a local store of semi-permanent data providing information on geographic features, aircraft and weapon characteristics, pre-planned missions and threat data. The ease with which all this data can be made available to the mission planning system is highly dependent upon the establishment of data standards, which should preferably be adopted throughout all the NATO countries and not confined to a single country or a single service.

The principal interfaces with the operator are provided by a conventional keyboard, a mouse or trackball and a high resolution colour display. The printer is usually capable of providing high quality colour maps for use during the mission, and hence has to be of a specially high standard.

The principal outputs from the type of ground-based planner shown in fig.3 are of two forms. First there is a folder which will be used by the aircrew which contains printed data concerning the planned mission together with the maps already referred to. In addition, the planner will output data about the mission plans in a digital form into a cassette which can then be linked into the aircraft's avionics system and so feed to it all the data required for the forthcoming mission. This cassette is also a means whereby data other than mission plans can be loaded into the aircraft, so the planning system is frequently designed to accept and process such data before it is transferred to the cassette and hence to the aircraft; an example of such data might be concerned with IFF codes. Similarly the systems can be used for downloading and subsequently processing data at the end of a flight (e.g. maintenance data on avionics and utility systems), This usage also increses the need for standardisation of data formats and has significant implications for interoperability.

3. DESIGN OBJECTIVES.

The continuing rapid advances in the techniques of mission planning have to be seen in the context of parallel advances in other areas of information technology, notably in on-board avionics systems and in communication networks. The primary function of a pre-flight mission planning system can then be considered as a process in which data is fused, filtered and compressed before being transferred into the on-board system for susbsequent in-flight use. With the increasing complexity of on-board systems, including particularly their incorporation of terrain-based information, the need for much improved mission planning systems becomes clear and inevitable, otherwise the planning process will be slow and difficult to use, and the data supplied to the on-board avionics system will be inadequate.

The key design objectives of such a system are typically:-

The generation of better optimised mission plans through-

- Improved effectiveness of the planning operation
- Better use of available data
- Improved data fusion and processing capabilities

Reduced planning times and workload through-

- Optimised aircrew interaction
- Effective network interfaces

The generation of information in appropriate formats for-

- On-board avionics systems
- Aircrew use during the mission
- Planning coordination through on-ground networks

Provision of briefing/debriefing facilities

Provision of rehearsal facilities

Maximisation of interoperability features.

Affordability and Reliability

4. PLANNING TASKS.

During the planning process a series of **tasks** have to be performed. A comprehensive literature review was conducted by Anacapa Sciences (Ref.4) which led to the preparation of a task-oriented model of mission planning. At the highest level, Anacapa Sciences identified the following seven tasks for an air-to-ground attack mission:-

1. assimilate target and weapons data
2. review threat and weather data in the target area
3. specify attack profile
4. optimize flight route
5. select aircraft configuration and procedures
6. review mission plan
7. transfer system data to aircraft

Each task can be further divided into subtasks, and it should be noted that the review **task** *(6)* may result in a return *to* one of the earlier tasks in an iterative routine. Each of these seven tasks is typically carried out by a combination of the operator working with the computer-based planning system. The increased power and sophistication of modern computers is facilitating the transfer of more of **the** work from the operator to the machine in such areas as routine calculations of speeds, timings, fuel consumptions and margins. In other areas, for example in the optimisation **task** (4), the state-of-the *art* in computer-based optimisation routines does not seem sufficiently mature to allow a fully automised process to be used and, in addition, the extent to which aircrew will be prepared to accept plans based on automated processes remains unclear at this time.

5. HUMAN FACTORS ASPECTS.

Human factors considerations are necessarily an important part of both the overall design strategy of mission planning systems and of many of the design details. The work-sharing between the computer and the operator has already been referred to, but although this is important there are other equally important issues which can only be decided by considering the total **tasks** of the aircrew and other persons involved.

Fig.5 illustrates the flow of information between man and machine during different phases before, during and after the execution of the mission. It also shows how information transfer is achieved before and after the mission. It is important to note that, prior to the flight, information is transferred into the aircraft by two mechanisms. As shown in fig.5 there is firstly the data which is transferred by cartridge or other means directly from the mission planning system into the aircraft's avionics system. Secondly there is the information carried on by the aircrew, both in the form of paper maps and other printed information,and also in the form of knowledge carried in the aircrew's memories. It is this latter which is frequently regarded as vital to mission success and is clearly dependant on the part played by the aircrew in the mission planning process. In-depth invovement by the aircrew in the planning process will certainly increase their knowledge of the mission strategy and the details of the plan. On the other hand, minimising their involvement will reduce their workload and fatigue prior to flying the mission. Another factor in this choice may be that non-flying planners may have wider experience which they can bring to bear in planning. Thus the choice betwwen specialist planners or participating aircrew to plan missions is certainly not clear-cut.

Fig.5 also shows that at the end of the flight it is necessary to extract data from both the aircraft and the aircrew in order to have the best information conceming the execution of the mission. This process of data extraction and analysis can also be expedited by using the mission planning system since many of the interfaces and the analysis tools are identical to those used prior to the mission.

6. MISSION REHEARSAL.

The advantages to aircrew of particiating in pre-flight mission planning have already been referred to, and these benefits can be deliberately enhanced by appropriate design of the mission planning system. Probably the best method of achieving this is by configuring the system to incorporate some level of mission rehearsal in the mission planning. By rehearsal is meant requiring the crew to carry out, in proper sequence (though not necessarily in real time), some of the functions which they would have to carry out during the actual mission. The parts of the mission which would normally be covered in such a rehearsal would usually be in critical phases such as target location and attack; other parts such as take-off and flying over friendly temtory would not be covered since normal training would give aircrew the knowledge and skills required for these phases.

The extent to which rehearsal is desirable or necessary is strongly affected by whether or not the aircrew have been able to train in scenarios similar to those of the mission being planned. At the time when much of NATO training in Europe was in expectation of a defensive battle over the same territory as that over which training was carried out, the training could take the form of rehearsal so the further rehearsal immediately prior to missions would not have been necessary. But the increasing likelihood of regional conflicts, to which reference has already been made, has increased the need for rehearsal as an integral part of mission planning.

To carry out rehearsal, some form of mission simulation must be provided. Just as with simulation for training purposes, the sophistication of the simulation can be at many levels: critical areas which profoundly affect both initial and operational costs are concerned with the simulation of the real-world scene and the need for real-time operation. These will be discussed in more details in the lectures which follow.

The concept of using a visual representation of the real-world scene during mission rehearsal is not a new one, as can be readily seen from Chester Wilmot's classic study of the 1944-45 battles in Europe (ref.5), and in particular his account of the airborne landings in Normandy. He describes how, for the briefing of British glider pilots and aircrews, the Army constructed a detailed model of the Ome Valley, correct even to the height of the trees and the size of the houses. From this model a film was made, which gave the impression of flying over the coast of France, following the precise route the gliders, tugs and troop-carriers would be flying. This was far more instructive than the study of static air photographs for, as they watched the film, the pilots saw features and landmarks as they came into view and learned what to look for. After they had seen the film several times with normal lighting it was screened again through a blue filter, which gave a faithful representation of moonlight conditions. The crews, knowing the landmarks, were then able to see which were most likely to be visible at night. Perhaps the most important benefit of this carefully executed mission rehearsal process was the confidence which it instilled in the participating aircrew.

7. THE PROGRAMME OF LECTURES.

Following this introduction, the eight lectures which comprise this AGARD Lecture Series are arranged in such a way as to form a coherent description of the state-of-the-art in Mission Planning.

The first lecture, on "Overall System Concepts", describes the system design issues inherent in mission planning systems. There follow two lectures on Human Factors which together cover the theory and the practical implementation aspects. The forth and fifth lectures are concerned with technologies used in mission planning systems; these cover the two important areas of computing and man/machine interfaces.

The last three lectures, which are presented on the second day, describe systems which are currently in development or have recently entered service which provide examples of three quite different types of system. These are, respectively, a ground-based system which can typically be used at squadron level, an in-flight system for use during missions as a pilot aid, and a large, complex mission rehearsal system.

It is recognised that, in this Lecture Series, it has not been possible to describe in detail all aspects of mission planning or provide examples of all the different types of system currently in service or in development. Nevertheless, it is believed that, taken together, the lectures will provide a fairly complete coverage of both the theory and practice of mission planning.

REFERENCES

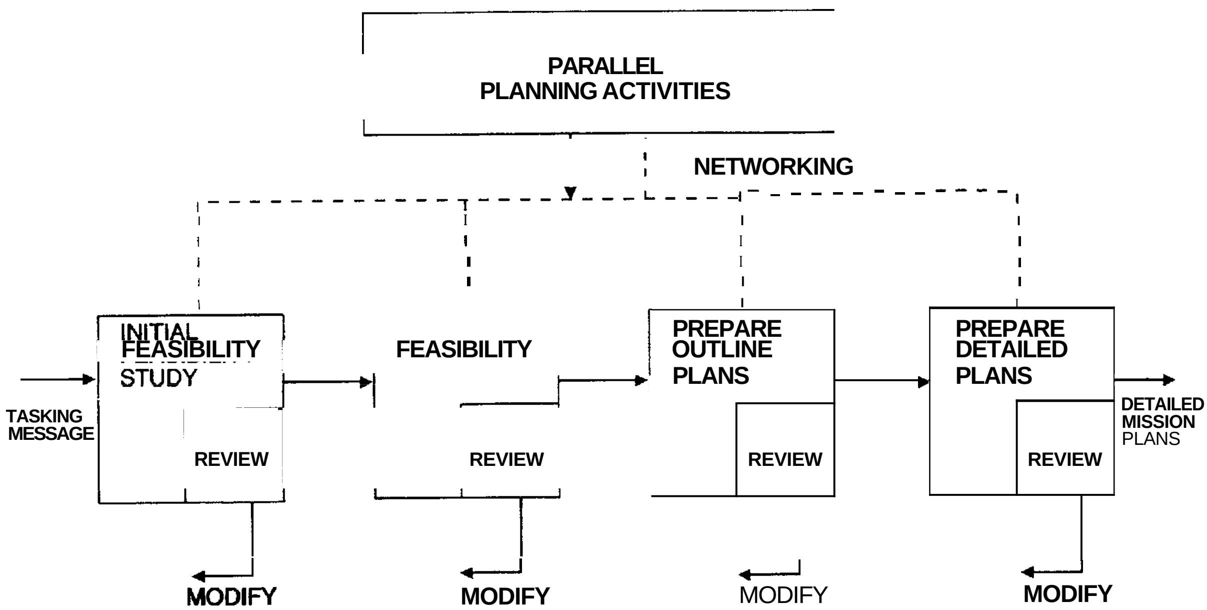
1. AGARD, Advisory Report 296 of Joint Working Group 15 on "Mission Planning Systems for Tactical Aircraft". 1991

2. **AGARD,** Advisory Report **313** of Joint Working **Group** 15 on "Mission Planning Systems for Tactical Aircraft". 1993

3. Carrington, Lord, "Reflect on Things Past", Collins, 1988

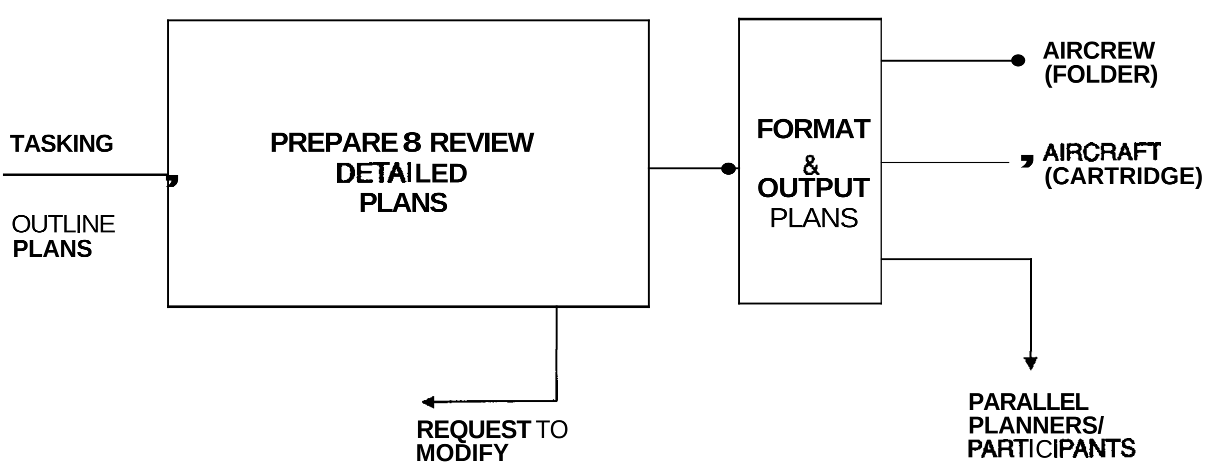
4. Anacapa Sciences Inc., "Functional Capabilities of Mission Planning Systems" Report 625-12, 1988

5. Wilmot, *C.*, "The Struggle for Europe", Collins, 1952



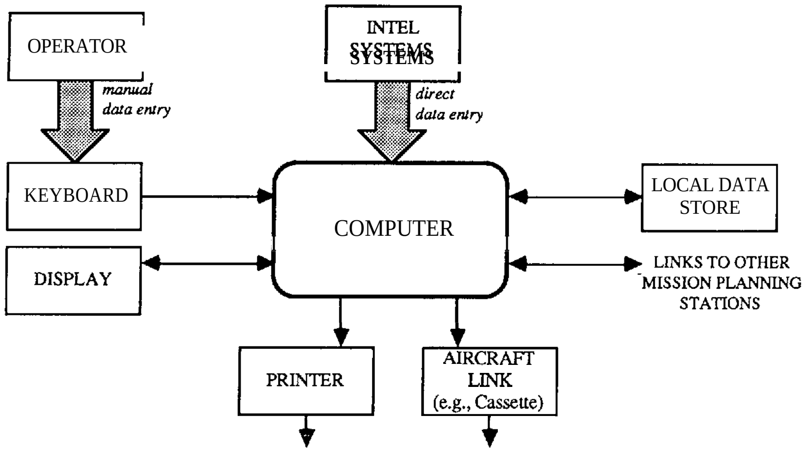
MISSION PLANNING **ACTIVITY CHART**

Fig.1



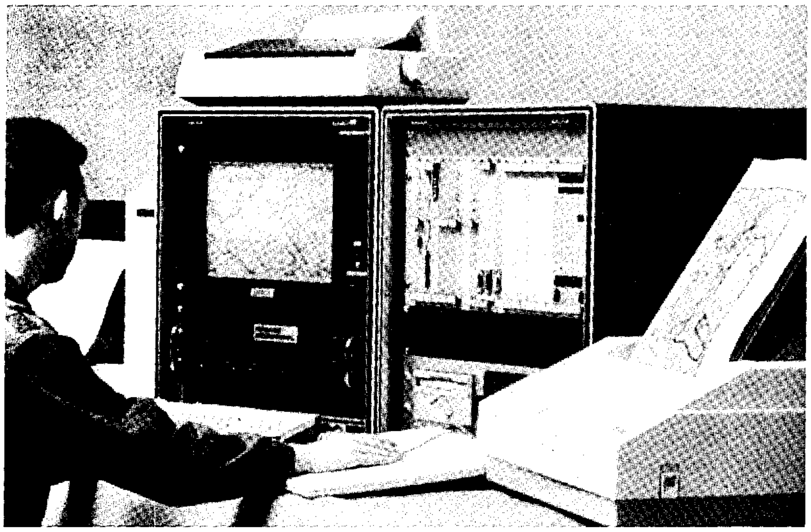
MISSION PLANNING SYSTEM FUNCTIONS

Fig.2



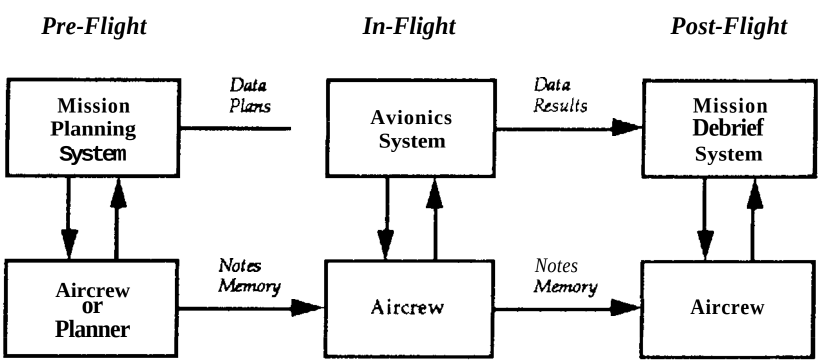
Schematic of a Typical Mission Planning System.

Fig.3



A Typical Mission Planning System

Fig.4



Transfer of Information Between Pre-Flight, In-Flight, and Post-Flight Phases.

Fig.5

Overall System Concepts in Mission Planning

by

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ABSTRACT

This paper describes fundamental system concepts useful in addressing future growth areas of mission planning systems called out in Section 2.1 of the AGARD Advisory Report 313 "Mission Planning Systems for Tactical Aircraft (Pre-Flight and In-Flight). A significant requirement for mission planning systems, especially for autonomous vehicles, is the ability to quickly plan and/or replan a complex task or mission. Fast, efficient re-planning is especially important because the state of the world can change abruptly and radically during the course of a mission. Mission planning systems must embody the capability necessary to swiftly replan actions in order to accommodate a vehicle's changing health or environment while continuing to pursue mission objectives. The complexity of mission planning problems has led to the use of hierarchical decompositions to make those problems manageable. The hierarchical approach to decision-making decomposes a large problem into a number of separate levels or sub-problems, thereby reducing the overall complexity, ideally without compromising overall system performance. In this lecture paper, an architecture for a mission planning system is presented with descriptions of the associated planning algorithms and planning management functions.

1. INTRODUCTION

1.1 Background

This paper describes fundamental system concepts useful in addressing future growth areas of mission planning systems called out in Section 2.1 of the AGARD Advisory Report 313 "Mission Planning Systems for Tactical Aircraft (Pre-Flight and In-Flight). The following is from Report 313:

"These future areas include:

1) integrating ground-based mission planning systems into networks that can perform mission planning at higher levels in the chain-of-command (e.g., squadron level or wing level).

2) fully integrating ground-based mission planning systems into C^3I networks so that they may fully exploit the latest real-time information concerning the battle-field situation.

3) moving towards greater amounts of automation in the mission planning process itself, where the mission planner is able to perform more sophisticated planning functions that currently are performed by the human planner.

4) moving automated mission planning technologies from the ground into the aircraft.

5) applying mission planning technologies to the growing field of Remotely Piloted Vehicles (RPVs), Unmanned Air Vehicles (UAVs), and Smart Weapons."

This lecture paper is based on work accomplished by a team at Draper Laboratory that includes Robert Beaton, Milton Adams, James Harrison, Owen Deutsch, Hueng-wah Leung, Mark Abramson, Jim Cervantes and Rami Mangoubi. Many sections of this paper are taken from a series of papers and reports written by one or more of these individuals.

1.2 Mission Planning System Requirements

A significant requirement for mission planning systems, especially for autonomous vehicles, is the ability to quickly plan and/or replan a complex task or mission. Fast, efficient re-planning is especially important because the state of the world can change abruptly and radically during the course of a mission. Mission planning systems must embody the capability necessary to swiftly replan actions in order to accommodate a vehicle's changing health or environment while continuing to pursue mission objectives.

Presented at an AGARD Lecture Series on 'New Advances in Mission Planning and Rehearsal Systems: October 1993.

The activities that must be performed by an aircraft during the course of a mission can be broken down into the following categories [1].

(1) *Preflight Check.* Minimal planning requirements.

(2) *Takeoff and Climbout.* Planning requirements for takeoff and climbout include coordination with Air Traffic Control and planning the climbout trajectory.

(3) *ingress.* Planning requirements during the ingress phase include planning the ingress route as well as planning the activity of sensors, weapons and ECM during the ingress.

(4) *On-station Activity,* Planning requirements for on-station activity consist of selecting and ordering the on-station activities and planning the use of sensors, weapons and ECM during the on-station activity. On-station activity can include a variety of mission objectives including ground attack, reconnaissance, supply, and Combat-Air-Patrol.

(5) *Egress.* Planning requirements during the egress phase include planning the egress route, as well as planning the activity of sensors, weapons and ECM during the egress.

(6) *Descent and Landing.* Planning requirements for descent and landing include coordination with Air Traffic Control and planning the descent trajectory.

(7) *Post-flight Debriefing.* No planning requirements.

Of the seven activities, the most critical, both in terms of mission success and in terms of the of planning requirements, are ingress/egress planning and the on-station planning. Both of these activities require two types of planning. The first type of planning concerns selecting the subset of mission objectives to be pursued and generating the aircraft's flight path. The second type of planning concerns planning the activity of the aircraft's sensor, weapon and ECM systems along the flight path, both during the ingress/egress and the on-station phases of the mission. The planning work that is described in this paper is concerned only with the first type of planning activity.

Given an aircraft, a set of potential mission objectives and a set of constraints placed on the pursuit of those objectives, the *Aircraft Mission and Trajectory Planning Problem* is to:

(1) select and order the subset of objectives that maximizes mission effectiveness while satisfying the constraints and

(2) generate the trajectories that allow the aircraft to reach the objectives safely and on schedule.

The inherent complexity of this problem is compounded by the fact that the state of the aircraft and its operational environment cannot be known with certainty and because the operational environment, the aircraft's flight capabilities, the mission objectives, and the constraints are all subject to change during the execution of the mission. The necessity to replan in-flight in real-time to accommodate contingencies that arise during the execution of the mission makes mission planning an especially challenging computational problem.

The aircraft mission and trajectory planning problem can be formulated as a *constrained, statistical optimization* problem. It is *constrained implicitly* by the physical limits of the aircraft's performance (fuel carrying capacity, performance envelope and subsystem capabilities). It is *constrained explicitly* by a planning authority that specifies mission constraints (probability of survival, mission objectives, scheduling and/or ordering constraints for the mission objectives). It is *statistical* in that uncertainties in the current and future states of the aircraft and the operational environment must be accounted for in the construction and evaluation of mission plans. Finally, it is an *optimization* problem in that the planning system is expected to generate plans of near-maximum mission effectiveness' which satisfy the specified constraints. Here, the utility of a given plan refers to the value that can be expected[2] to accrue if that plan is selected for execution.

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1 The computational complexity of the aircraft mission planning problems makes it impossible to guarantee finding the most effective mission plan in the limited time available for planning in real-time.

2 The utility of a plan is computed as a statistical expectation, where the expectation is computed over a distribution

A *mission plan* consists of the ordered sequence of objectives under a specific set of constraints along with a set of trajectories defining the flight path to be taken between each pair of objectives. Consequently, a natural method of approaching the aircraft mission and trajectory planning problem is to decompose the problem into two parts called the Trajectory Planning Problem and the Mission Planning Problem.

2. HIERARCHICAL DECOMPOSITION

The complexity of mission planning problems has led to the use of hierarchical decompositions to make those problems manageable [2]. At Draper Laboratory, hierarchical planning and scheduling architectures have been developed for various applications including: layered control architectures for autonomous submersibles [3]; hierarchical planning management architectures for helicopter nap-of-the-earth missions [4]; and hierarchical planning and scheduling architectures for railroad traffic control [5]. For each of these activities, the design objective has been to develop an architecture which allows the complex planning and scheduling problem to be decomposed into manageable subproblems. The architecture must support the flow of information (commands, resource requests, and status reports) throughout the system that is required to support the orderly execution of the planning process. Mission and trajectory plans are developed within the hierarchy to optimize a selected objective function (e.g., to minimize lethality, fuel or time, or to maximize mission accomplishment) subject to constraints that must be satisfied by the plans (e.g., allocations on mission time, survivability or weapons use).

2.1 Multi-Level Optimization

This section presents mathematical background for multi-level optimization needed to solve hierarchically decomposed complex problems, such as those described above.

Key to any hierarchical decomposition is the proper coordination of subproblems in order to ensure that the system-wide objectives and constraints are optimized and honored, respectively, through the solutions of the individual subproblems. Indeed, this is the principal goal of multi-level, hierarchical decomposition of optimized planning problems [6, 71.

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that reflects the uncertainty in the vehicle state and the operational environment.

The intent of multi-level optimization is to decompose a complex optimization problem into a hierarchy of simpler problems. The simpler optimization problems are solved independently at each level of the hierarchy, with the upper levels coordinating the solutions of the decoupled lower level problems. The discussion here of multi-level decompositions is intended to be qualitative. Technical details and conditions can be found in [6, 7,8]. Consider the typical problem statement:

$$\min_{\underline{x},\underline{y}} f(\underline{x},\underline{y})$$

subject to $\underline{g}(\underline{x},\underline{y}) \leq \underline{0}$;

where $\underline{x} = [\underline{x}_1\ \underline{x}_2\ \dots\ \underline{x}_N]^T$

The vector $\underline{x}$ is composed of subvectors $\underline{x}_i$ which will be associated with the N subproblems at the lower level, and the vector $\underline{y}$ corresponds to the variables that couple the subproblems either through the objective function f or the constraint vector $\underline{g}$. The problem can be rewritten in terms of a Lagrangian L with Kuhn-Tucker multiplier vector $\underline{\gamma}$ [8]:

$$L(\underline{x},\underline{y}) = f(\underline{x},\underline{y}) + \underline{\gamma}^T \underline{g}(\underline{x},\underline{y})$$

The decomposition of the optimization problem is achieved by creating an upper level problem that either sets the value of the coupling vector $\underline{y}$ or the value of the multiplier $\underline{\gamma}$. The former is referred to as "interaction prediction" and the latter as "goal coordination" or "price coordination" [6,7]. It is assumed that in setting the value for the coupling variables that the Lagrangian can be rewritten as a sum of decoupled Lagrangians L_i (i.e., setting a value for $\underline{y}$ leads to separability of both the objective function f and the constraint vector $\underline{g}$):

$$L(\underline{x};\underline{y}) = \sum_{i=1}^{N}[f_i(\underline{x}_i;\underline{y}) + \underline{\gamma}_i^T \underline{g}_i(\underline{x}_i;\underline{y})] \equiv \sum_{i=1}^{N} L_i(\underline{x}_i;\underline{y})$$

In this case, given values for $\underline{y}$, each of the N lower levels is responsible for solving a decoupled optimization problem associated with a sub-Lagrangian L_i:

$$\min_{\underline{x}_i} f_i(\underline{x}_i;\underline{y})$$

$$\textbf{subject to } \underline{g}_r(\underline{x}_i;\underline{y}) \leq \underline{0}$$

Typically, iterations between the upper and lower levels are required to achieve an optimal solution.

2.2 Application to Mission Planning

Planning algorithms and the associated planning management functions are needed to provide intelligent aid to the decision maker — whether human (in semi-autonomous vehicles) or machine (in autonomous vehicles) — to plan and execute a mission and to modify activities in real-time in response to unforeseen events [9]. Given a well-defined planning problem (i.e., objectives, constraints and knowledge of the mission environment) *Planning Algorithms* produce a plan of actions that would best achieve' the specified objectives within the specified constraints for the specified environment. *Planning Management Functions*[3] monitor the progress of the plans currently being executed to decide if re-planning is necessary and, if so, define the revised planning problem to be solved by the planning algorithms. In effect, planning management functions *manage* both the planning process and the execution of plans, acting as the interface between the mission planning algorithms and other onboard systems such as fault detection and isolation, redundancy management, sensing and imaging systems, navigation, and control. Much of the effort invested in automation for autonomous vehicles during the past decade has been in the development of planning algorithms for a variety of mission applications. In contrast, little investment has been made in formalizing the development of the associated planning management functions that are a prerequisite to successfully fielding planning algorithms in operational autonomous and semi-autonomous vehicles.

Within a planning system, the level of detail to which mission activities must be planned by a given planning algorithm is determined by spatial and temporal planning horizons. Over a short planning horizon, actions must be planned in great detail. In contrast, it is unnecessary, even futile, to plan actions that lie beyond a short planning horizon at the same high level of detail. Thus, there is a natural decomposition of the planning function into a *hierarchy of planners,* wherein the planning horizon decreases and the level of detail at which actions are planned increases as one moves from higher to lower levels of the hierarchy. In the context of an aircraft mission planning problem, skeletal plans of the entire mission are constructed at the highest level of the hierarchy *(Mission* level). **At** intermediate levels (*Route/Activity* levels), near-term actions that are consistent with the strategic plan are planned in greater detail. Finally, at the lowest level of the hierarchy *(Flight Safety* level), commands are generated for vehicle subsystems (e.g., sensors, vehicle propulsion and control systems) that execute the mission and ensure vehicle safety. Figure 3-1 illustrates plans generated by a hierarchy consisting of three levels for an aircraft example. The uppermost panel of the figure depicts the potential mission objectives set forth in the mission requirements, threat regions that are known *a priori*, and zones within which vehicle travel is restricted. Typical plans generated by several levels of the planning hierarchy are illustrated in the other panels of Figure 3-1. These are discussed in more detail in succeeding sections.

3 Planning Management Functions include what are traditionally referred to as Mission Management Functions. The term planning management is employed to focus attention on their role in managing the onboard mission planning.

3. MISSION PLANNING AND MISSION MANAGEMENT

3.1 The Planning Problem

The hierarchical approach to decision-making decomposes a large problem into a number of separate levels or sub-problems, thereby reducing the overall complexity, ideally without compromising overall system performance. At the top level of the hierarchy the entire mission is planned using coarse (e.g., abstract) models. **As** one progresses downward in the hierarchy, the spatial and temporal scope of the decision-making functions decrease and the level of modeling detail increases. The partitioning of the problem into subproblems, the specification of appropriate local performance criteria, and the modeling of the interactions among subproblems are all part of an integrated approach to developing a hierarchical decomposition. An important goal of this decomposition is to maintain a balance in the complexity of decision-making effort across all levels of the hierarchy.

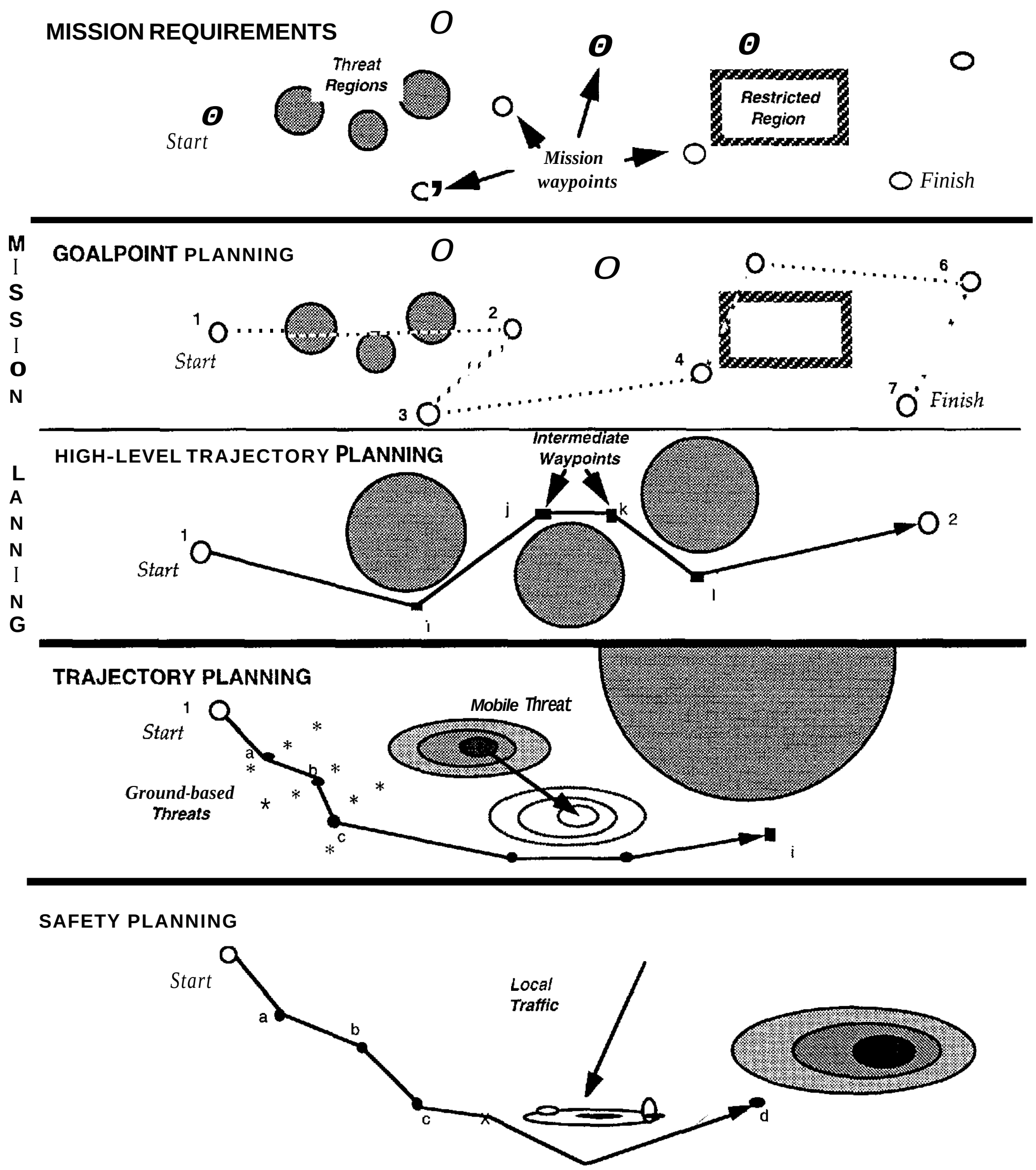

Figure 3-1. The Planning Hierarchy. The planning problem is made tractable by decomposing it into a hierarchy. At the top level of the hierarchy the entire mission is planned using coarse (e.g., abstract) models. As one progresses downward in the hierarchy, the spatial and temporal scope of the decision-making functions decrease and the level of modeling detail increases.

The planning system described in this paper consists of a hierarchy of ***planners*** which collectively cooperate to solve mission planning problems. Each planner consists of a number of components: planner-specific data, models, reasoning mechanisms (algorithms) and control mechanisms (management functions). The levels of abstraction of each of these planner components vary from level to level within the hierarchy, but must be self-consistent at any given level. The control mechanisms not only control the planning algorithms at each level of the hierarchy but also the flow of information and control among the various planners in the hierarchy. This ensures that the planning process proceeds in an orderly fashion. Thus, each planner within the planning system provides planner-specific outputs to, and accepts planner-specific inputs from, other planners within the hierarchy.

3.1.1 Planning vs. Management.

As described above, there are two principal functional elements embedded in each level of a planning system hierarchy, planning algorithms and planning management functions. The **planning management functions** control plan execution, manage interactions among adjacent levels of the planning hierarchy, and implement re-planning decision logic. The **planning algorithms** develop plans whenever the planning management functions have decided that re-planning is appropriate. The hierarchical decomposition of the aircraft goal-point and trajectory planning problem is discussed in Section 3.1.2. Each of the planning management sub-functions is described in Section 3.1.3. The interfaces between the planning algorithms and the associated planning management functions are discussed in Section 3.2.

3.1.2 Hierarchical Decomposition of Automated Mission Planning

To make our discussions concrete, a specific hierarchical decomposition of the vehicle mission planning problem has been selected. The selected planning system hierarchy has three levels: the *mission level*, the *route/activity level* and the *flight safety level* (see Figure 3-1). The nature of the plans and the planning algorithms that are used to generate plans at each of these levels are described below.

Two types of waypoints are referred to in the discussions of planning algorithms: mission waypoints and intermediate waypoints. *Mission waypoints* are associated with mission objectives and are specified as inputs to the planning system. *Intermediate waypoints* are waypoints that are generated at the discretion of the planning algorithms. They are used to define the trajectories between selected mission waypoints. Intermediate waypoints can be added to or deleted from the mission plan by the planning algorithms.

3.1.2.1. Mission Planning Level

At the mission planning level the selection and ordering of a subset of mission waypoints that make up the nominal mission plan and the definition of the trajectories between the mission waypoints at a low level of resolution [10,11] are performed. The mission planning problem is decomposed into a *high level trajectory planning problem* and a *goalpoint planning problem*, each with an associated planning algorithm. A by-product of the plans generated at the mission planning level is the resource allocation spanning the complete mission that is consistent with the overall mission resource budget.

3.1.2.1.1. High Level Trajectory Planning Algorithm

The high level trajectory planning algorithm generates near-optimal (within specified constraints on time, energy and survivability) trajectory segments between mission waypoints. In a pre-mission planning mode, the high level trajectory planning algorithm generates a set of trajectory segments linking all pairs of mission waypoints. During a mission, some or all of these trajectory segments may be updated at the discretion of the planning management functions to accommodate changes in the expected mission environment (e.g., weather and threats). In our implementation, trajectory segments are generated by a modified **A*** search over a predefined set of candidate mission waypoints [11]. The **A*** search methodology has been selected because it provides a computationally efficient mechanism for making trade-offs between solution optimality and search time. In generating trajectory segment s between mission waypoints, the A* search employs lethality models for anticipated threat encounters and energy consumption models that account for vehicle airspeed, altitude, altitude rate and winds. The high level trajectory planning algorithm accommodates (1) moving air traffic (multiple vehicles), (2) winds and weather systems, (3) ground-to-air threats, (4) specific criteria for waypoint capture and (5) corridors bounding trajectory segments between specified mission waypoint pairs. The trajectory segments, together with estimates of the costs that would be incurred in pursuing them, are stored in a trajectory buffer for subsequent use by the goalpoint planning algorithm.

The A* search methodology makes it possible to obtain multiple solutions (i.e., multiple segments between a given pair of mission waypoints), each corresponding to a different optimization criterion and/or set of constraints. This provides the goalpoint planning algorithm described below with a set of trajectory segments that trade off time, energy and lethality in different ways.

3.1.2.1.2. Goalpoint Planning Algorithm

The function of goalpoint planning is to use the high level trajectory segments and their associated cost (resource usage) information to construct a mission plan. This is done by selecting and ordering the subset of mission waypoints (objectives) that maximizes the utility of the mission plan under specified constraints. In our implementation, the goalpoint planning algorithm is initialized with a seed plan, typically a degenerate plan consisting only of the origin and final destination of the vehicle. This plan is iteratively improved through a number of modification cycles [10,11]. During these modification cycles, the best plan found during all previous cycles is stored in a *best plan buffer*. Within each cycle, the plan representing the initial condition for that cycle is modified in accordance with a set of heuristics. The output of this process, the mission plan consisting of the selected mission waypoints and high level trajectories, is placed in theflight *plan buffer*, which contains the plans that are generated at all levels of the hierarchy.

3.1.2.2. Route/Activity Level

The route / activity level of the hierarchy is responsible for filling in details in the plan generated at the mission level. Two classes of plans are generated at this level: more detailed *routes* between the intermediate waypoints that are specified in the the high level trajectory plan segments and *activity plans* required to accomplish the mission objectives associated with each of the mission waypoints specified by the goalpoint plans. The objectives, resource allocations, timelines etc. for generating these route and activity plans are all contained in the plan generated at the mission level. These plans have a shorter spatial and temporal horizon than the plans generated at the mission level. In order to perform planning at this level, the mission environment must be described at a higher level of detail than is required at the mission level. A more detailed description of the mission environment is obtained by fusing onboard sensor data with a priori map data.

A brief description of a route planning algorithm is given below. Since the nature of the activity planning algorithms will vary significantly as a function of the designated mission objective (e.g., reconnaissance, supply, ground attack, interdiction, etc.), no activity planning algorithm is described.

3.1.2.2.1. Route Planning Algorithm

The primary function of route planning at this level of the hierarchy is to plan the vehicle's flight path at a higher level of detail than is provided by the intermediate waypoints of the high level trajectory segments specified at the mission planning level. The route planning algorithm produces detailed plans, consisting of a set of intermediate waypoints that are consistent with both the resource allocations established by the mission plan and the vehicle's performance envelope. The inputs to the route planning algorithm are the mission plans stored in the flight plan buffer and the current best estimate of the state of the mission environment supplied by the information fusion function. The output consists of route plans connecting a pairs of mission waypoints or intermediate waypoints defined by the high level trajectory plan. The route/activity planning algorithms[4] are required to generate plans that: (1) adhere to flight corridors and mission specifications, *(2)* avoid local storm systems and adverse winds, (3) avoid collisions with local air traffic, (4) avoid collisions with the ground, (5) account for vehicle system failures or damage and *(6)* specify the utilization of sensor and payload systems.

In our implementation, plan generation is accomplished by a near-optimal **A*** search similar to that used by the high level trajectory planning algorithm of the mission planner. A major difference between the functions of the route / activity and mission planners is the information used by each in generating plans. The mission planner uses *a priori* and communicated map data. Because the route/activity planners generate plans incorporating greater detail and for shorter temporal horizons than the mission planner, the route planning algorithm requires both real-time sensor data and a priori data for generating its plans

3.1.2.3. Flight Safety Level

During the execution of the nominal mission plan, events that have not been anticipated in formulating the nominal mission plan and which threaten the safety of the vehicle may occur. The planning hierarchy accommodates these events at the lowest level of the hierarchy (see Figure 2) where near-term flight safety plans are generated. These plans take precedence over any other plans in the near-term.

The primary function of the flight safety planning algorithm is to provide a plan, over a very short temporal horizon, that is guaranteed to meet survivability requirements. Secondary emphasis is placed on time and fuel optimization. The fact that the flight safety planning algorithm is invoked is an indication that more reasoned approaches could not be used to obtain a plan in time to accommodate the current safety threatening situation. Inputs to the flight safety planning algorithm are contained in the flight plan buffer (the mission plan, route plan and possibly an active flight safety plan) and the current best estimate of the state of the local mission environment. As with the route planning algorithm, the flight safety planning algorithm

4 More than one algorithm may be required to meet these requirements.

depends heavily on fused real-time sensor data for knowledge about the state of the world. The detail of the flight safety plan is comparable to or higher than that of the route planning level. The flight safety planning algorithm produces a plan that is executable within the vehicle's performance envelope and that ensures a flight path that is within an acceptable risk of vehicle loss. The output may either be a complete flight plan to the next intermediate waypoint generated or a plan whose temporal horizon allows sufficient time for more reasoned planning to regenerate the trajectory to the next intermediate waypoint.

3.1.2.4. Planning Management.

Whereas planning algorithms generate the specific sequences of actions that define a mission plan, *planning management functions* monitor. the current situation for events that may require a re-planning response, determine the nature of that response by defining the inputs to the planning algorithms, and control the interactions among the several levels of planning. The planning management functions play the role of an executive that:

(1) monitors progress relative to the execution of the current mission plan and assesses the vehicle's ability to continue to successfully execute the current plan,

(2) monitors the current situation for changes in the state of the vehicle or mission environment that may necessitate a re-planning response

(3) monitors any changes in mission objectives or constraints that may necessitate a re-planning response

(4) determines the nature of the re-planning response by selecting the appropriate planning algorithms and defining their inputs

(5) controls the interactions among the several levels of the planning hierarchy to coordinate the planning effort.

Note that it is possible to implement the monitoring functions described in items 1-3 above within the information fusion function; however, this is generally undesirable because the monitoring functions are mission related and of broader scope than the information fusion tasks of estimating the state of the vehicle and its operational environment.

3.2 The Architecture

The multi-level, distributed planning system architecture depicted in Figures 3-2 and 3-3 has been developed to implement the algorithms described in Section 3.1.2 and their associated planning management functions. Within this architecture, the planning management function is partitioned into modular sub-functions and distributed throughout the hierarchy. Each level is self-contained and has its own set of planning algorithms.

The management functions at each level make decisions based on three sources of inputs: the *mission manager databases*, which contain information about the state of the aircraft, the state of the environment and the mission objectives and constraints; the *flight plan buffer*, which contains the current plans developed at each level of the planning system; and *direct communication* from managers at adjacent levels, or, in the case of the mission manager, direct communication from a planning authority specifying changes in planning requirements.

The modular, distributed implementation of the planning management functions facilitates changes at any level of management without affecting the whole system. In addition, while each level of management performs similar functions and has similar interfaces, the modular structure allows each level to be tailored for planning activities specific to that level.

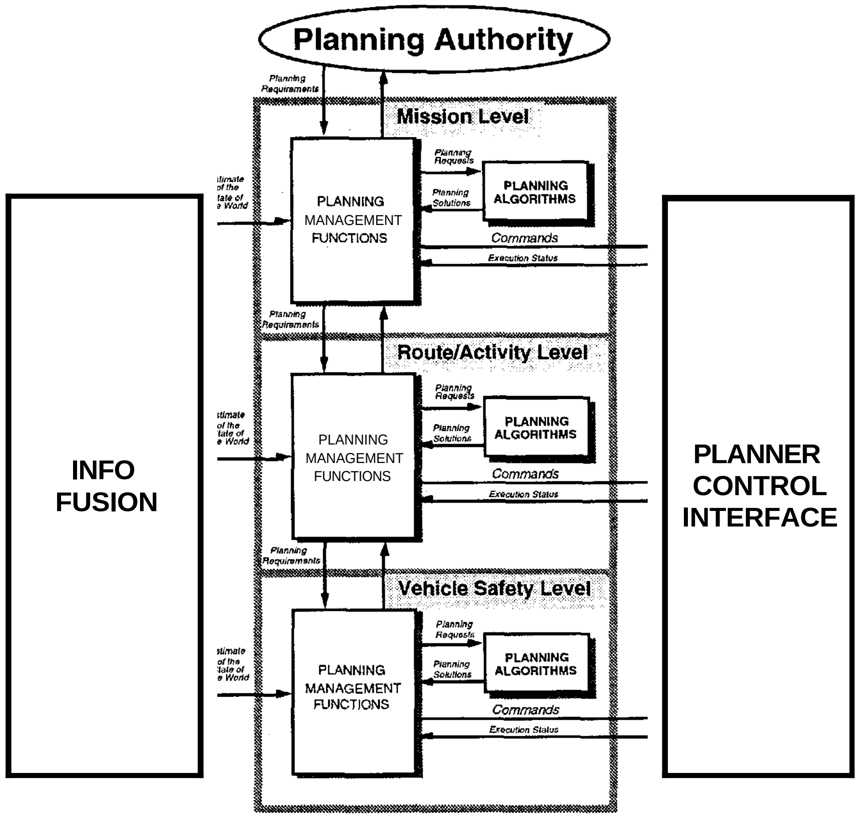

Figure 3-2. Hierarchical Planning System Architecture. The aircraft planning problem is decomposed into three layers. The mission planning level selects and orders the mission objectives and generates coarse trajectories between them. The route/activity level generates detailed trajectories for circumnavigating local environmental phenomena (e.g., storms or threats) and plans the activity of the vehicle sensors and payload subsystems. The vehicle safety level identifies situations that threaten the safety of the vehicle and generates appropriate responses (e.g., collision avoidance).

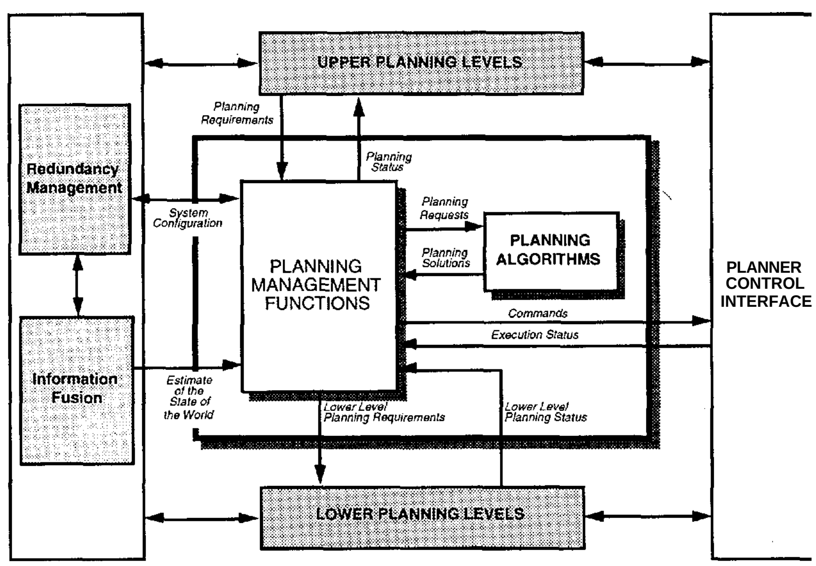

Figure 3-3. Generic Level of the Planning Hierarchy. Each level in the hierarchy is controlled by the planning management functions. Their primary function is to monitor the evolution of the current plan and decide if and when re-planning is necessary. Re-planning is accomplished by tasking the planning algorithms.

3.2.1 Management Functions.

The primary role of the planning management functions is to control the planning process at each level of the hierarchy. In order to achieve this objective, four classes of management functions must be implemented for each level of the hierarchy:

(1) Plan execution functions

(2) Plan monitoring functions

(3) Re-planning decision functions

(4) Inter-level coordination functions.

Each of these is discussed in detail below.

Plan Execution Functions.

Communication between the planning system and the vehicle guidance and control functions, sensors and payloads is buffered by the *planner-control interface* block in Figures 3-2 and 3-3. The plans developed by the planning algorithms at any of the planning levels contain two kinds of information. One describes activities that are to be executed by the guidance and control functions, sensors or payloads. The other defines requirements for lower levels of planning. The content of the plan describing guidance and control, sensor or payload activities must be translated by the planner-control interface into formats that are understood by the subsystems. Once translated, these activities are executed by the appropriate subsystems, and the progress of that execution is monitored. Both the current progress of plan execution as well as the impact that the current progress may have on the vehicle's ability to successfully accomplish activities planned for the future are monitored. These and other monitoring functions performed by planning management are discussed below.

Plan Monitoring Functions.

Monitoring Plan Execution. Associated with each mission plan is a measure of its expected value, referred to here as its utility, and its expected resource utilization profile. Thus, the progress of the execution of the current plan can be measured along two dimensions, utility and resource utilization. The actual utility is compared with the expected utility; the actual resource utilization profile is compared with the planned profile. If the actual utility or the actual resource utilization profile differs significantly from what is expected, then planning management may initiate re-planning. If the expected cumulative resource utilization exceeds the available onboard resources, then re-planning will produce a new plan that can be accomplished with the available resources. If the actual resource utilization is lower than that predicted by the expected utilization profile, re-planning might be invoked in an attempt to exploit surplus resources to produce plans of greater utility than that of the current mission plan. Part of the design of the planning management function is the selection of the decision thresholds that are used in the comparisons between the actual and the predicted values. Mechanisms must be established for communicating the results of plan monitoring to provide status information to superior levels of the planning hierarchy.

Monitoring Mission Objectives and Constraints Execution. Any changes in either the mission objectives (goals) or explicit mission constraints are made through a user interface by the pilot/crew in a piloted vehicle or through communications from a higher planning authority for an autonomous or semi-autonomous vehicle. Changes of this type will result in modifications to the mission requirements database and will result in an associated request to replan. These changes will have the most significant impact on planning at the mission level. In addition, it may be desirable to have the ability to externally override the planning functions, allowing the mission plan to be controlled manually. This capability would be useful during initial flight demonstrations of autonomous planners since it provides a mechanism for backup manual control as well as for testing specific flight plans, trajectories and vehicle maneuvers. This point is elaborated upon in Section 3.2.3.

Monitoring Vehicle and Environment Status. Planning management functions are required in order to monitor the status of both the vehicle and the mission environment in order to detect changes that may affect the vehicle's ability to successfully execute the current mission plan. This monitoring is event-driven and is based on information received from the information fusion function and its redundancy management sub-function. In our implementation, the decision to initiate re-planning in the face of events of this type is made by comparing the a priori plan utility with the expected utility conditioned on the given event.

The two primary classes of changes in vehicle status that may trigger a re-evaluation[5] of the

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5 The evaluation will be based primarily on the expected utility of the current plan

current mission plan are failures and damage to the vehicle. For redundant systems, a failure may result in an immediate loss of *performance* as well as in reduced subsystem *reliability* (e.g., one channel of a triplex system goes down). Here, performance refers to the vehicle's dynamic capability (i.e., performance envelope), sensing capability or payload *system's* capability. Reduced system reliability implies a lower probability of having the capabilities required to successfully accomplish future mission objectives. The planning management functions employ an onboard system reliability model to predict the probability of the future availability of specific vehicle subsystems given the current failure status of those subsystems. These reliability predictions are incorporated into the computation of the expected level of accomplishment of candidate mission plans. For example, a decision to abort a mission would depend significantly on the number of redundant elements that have been lost due to failures or damage and the impact of the failures or damage on system reliability.

Features of the mission environment that may impact the expected utility of the current plan are weather (winds/storms), threats and local air traffic. Timely information regarding these features of the mission environment must be supplied by the information fusion function.

Once a *significant* change in the state of the vehicle or environment has been detected by the planning management functions, one of several events may occur: (1) re-planning may be immediately initiated, *(2)* the plan may be re-evaluated in the face of the detected change and on the basis of that re-evaluation a decision to replan can be made or (3) re-planning at a high level may be delayed because it has been decided that a lower level planner should respond (or is responding) to the change.

Onboard Vehicle Performance Models. Onboard vehicle performance models are used in evaluating candidate plans and in detecting degraded vehicle performance. When failures, damage, or other potential performance degrading events occur, these models must be updated. Performance monitoring and modeling take place over both short and long time scales and at various levels of abstraction. The updated models developed are used to decide whether mission re-planning may be necessary, If it is, the updated models are used in building the new plan and allocating resources

given the current estimates of the state of the vehicle and environment.

across the time span of that new plan. Models are also used in emergency situations to evaluate the immediate impact of unidentifiable failures on the performance of the vehicle and its subsystems. These may be simple input-output models that provide approximate responses to specific commands.

The success of performance modeling requires appropriate interaction with mission planning/management. For example, in order to identify or update models of vehicle performance, specific vehicle maneuvers may be required in order to identify failed actuators or to "excite" the proper vehicle modes to identify and model the performance degradation due to ineffective aero-surfaces.

Examples of areas where performance monitoring and updating are important from the point of view of both fault tolerance and mission planning/management are:

- Vehicle fuel consumption as a function of flight condition
- Vehicle turn / climb / descend capability
- Vehicle speed response
- Sensor subsystems performance
- Payload subsystems capability

Re-planning Decision Functions.

Given inputs from: **superior levels** regarding plan requirements, **subordinate levels** regarding planning and plan execution status, the **planner control interface** regarding plan progress, and **information fusion** regarding the state of the vehicle and the mission environment, the planning management functions at each level must decide whether to continue to pursue the current plan that is being executed at that level or to replan. Given that a decision has been made to replan, inputs must be developed for the planning algorithms. In effect, those inputs define the problem to be solved by the planning algorithms. Included in those inputs are the constraints or resource allocations that must be satisfied by the plan (e.g., allocations on mission time, fuel, survivability, and weapons use) as well as the objective function that should be optimized in developing the plan (e.g., minimize lethality, minimize fuel, minimize time, maximize effectiveness). In cases for which there are multiple objectives, the management functions must establish the relative importance among those objectives. Finally, given that re-planning must be performed in real-time, the management functions must decide how much time is available for planning and how the onboard computational resources should be allocated in generating a new plan.

Reconfiguration/Recovery from Failures.

Planning management plays a joint role with redundancy management in reconfiguration and recovery following failures. For a given phase of a mission, the best configuration of the aircraft's hardware and software depends on the objectives that are to be accomplished during that phase. In addition, recovery from failures can be aided by the lowest level of the planning hierarchy in that the lowest level specifies short term flight trajectories requiring only the most stable flight modes immediately following a significant failure or damage event.

In the event of a failure, the primary objective of redundancy management is to configure the vehicle to ensure stability and safety of flight. Having insured that, redundancy management provides the planning system with information regarding the status of onboard systems and the range of vehicle capabilities that are possible given that status. The planning systems must take this information into account in developing new plans. Given a newly formulated plan, the planning system apprises redundancy management of the associated vehicle capability requirements, the redundancy management function then configures the non-failed vehicle subsystems in a manner that best realizes those capabilities.

For aircraft operations, it is important to distinguish between two types of failures that require redundancy management. One type consists of those failures that impact flight safety. These types of failures (e.g., actuator failures, computer failures) represent a threat to immediate safety of the aircraft. The second type consists of those failures that impact mission effectiveness. These types of failures (e.g., payload failures, sensor failures) do not pose a threat to the safety of the aircraft but they may impact the mission. For safety related failures, redundancy management is performed using standard techniques. However, for mission related failures, redundancy management must be performed in the context of the current mission situation, that requires interaction with the planning management functions.

Meta-Planning.

Each of the monitoring functions described above provides information that is used to decide whether or not to initiate re-planning. *Meta-planning* literally translates to "planning about planning" and here refers to the way in which the process of generating a new plan is controlled. Some of the elements of meta-planning relate to determining the level(s) of the hierarchy at which re-planning should be performed, deciding which planning algorithm to employ at a given level, and establishing the time allocated to generating a new plan. The last section of the paper proposes a method for modeling the planning process that provides insight into how to formulate a "control law" to insure stability of the planning process.

Planning management must be able to distinguish between small departures from the current mission plan that can be corrected by making small perturbations to that plan (e.g., changes in commanded airspeed) at the route planning level and significant departures that can only be corrected at the highest level of the planning hierarchy. For example, meta-planning may initially restrict the mission planning level by requesting that it first attempt to resolve any problems locally before attempting complete re-planning of the mission level plan. Discriminating between small and significant departures from plans generated at all levels of the hierarchy is a principal meta-planning function. For small departures, the planning algorithms may be directed to initiate re-planning using the current plan, potentially reducing the time required to find a good new plan. For large departures, re-planning may begin with a default "empty" plan, requiring the new plan to be completely rebuilt.

Inter-level Coordination Functions.

In a hierarchical system, higher levels provide guidance to lower levels. In the planning system, the plans generated at higher levels define both constraints and objectives that serve as requirements for planning at lower levels (see Figure 3-2). Planning management is responsible for translating that information into requirements for lower levels. At each subordinate level, those requirements must be properly interpreted for input to the planning algorithms at the subordinate level. In addition, each subordinate level must provide information to its superior regarding the status of the execution of the plans that are generated at that subordinate level. The primary flow of information within the planning hierarchy is that requirements drive the planning process from higher levels to lower levels, while the changes in the operational environment drives the planning process from lower levels to higher levels.

3.2.2 Implications for the Design of Planning Algorithms.

Isolating the Planning Algorithms.

One of the primary objectives of the design of the architecture depicted in Figures 3-2 and 3-3 has been to make a clear distinction between reasoning mechanisms and control mechanisms, i.e., between planning algorithms and the management functions. The architecture has been defined in a manner that provides clean interfaces between the planning algorithms and the planning management functions. The major benefit of this approach is that it simplifies the already difficult task of designing the planning algorithms by ensuring that management issues need not be addressed by the planning algorithms themselves. In addition the planning algorithms are packaged in a modular fashion that facilitates the insertion of new algorithms and allows one planner to call another (see Section 4) without consideration of potential management side effects.

Time to Plan.

In order for the hierarchy to perform effectively in real time, the time allocated to a given planning algorithm for a specific planning task must be established by the planning management functions. Constraints on time to plan may be defined at a given level or may be passed down from a higher level. In addition to the objectives and resource constraints that define a planning problem, each planning algorithm also requires an initial state as an input. Indeed, every plan must begin at a point in both space and time that is reflected in its initial condition. Choosing that point in the future implicitly bounds the time available to plan. Thus, the planning management functions at each level are responsible for coordinating the choice of an initial condition on the planning process with the planners at other levels. Furthermore, the planning management functions must decide which planning algorithms may be most appropriate given the available time to plan. Establishing the time to plan and associated planning initial conditions is a non-trivial decision-making problem; one that is crucial to the overall performance of the planning system.

3.2.3 Levels of Autonomy.

The ***level*** of *autonomy* of an automated planning system can be measured in terms of the frequency of operator interaction with that system and the complexity of those interactions. The more frequent and complex the interactions, the lower the level of autonomy. A vehicle capable of operating at several levels of autonomy provides an effective mechanism for ***testing and evaluating*** the performance of autonomous planning and decision-making functions without incurring the risks of completely autonomous operations. It also provides the capability for initially ***operating*** an autonomous vehicle at a low level of autonomy, while facilitating a gradual transition to the ultimate objective of complete autonomy. The planning management functions serve as the interface between the onboard, automated systems and the human operator (see Figure 3-4).

In order to design planning management functions that permit operations at multiple levels of autonomy, it is useful to partition the planning management functions in a way that is natural to human decision-makers. The execution, monitoring and re-planning decision-making functions described in the preceding sections represent such a partitioning. The information flowing into those partitions and the types of decisions they produce as outputs will be the same whether the decisions are made autonomously or by a human. In the case of the operator-in-the-loop, the presentation of the input information to the human decision-maker is provided through an appropriate user-interface. Partitioning the decision-making in this manner provides the additional benefit of making the autonomous decision logic easier to test, debug and evaluate, since the human tester can participate directly in the tests via the interface designed for person-in-the-loop operations.

The design of the planning management functions should be structured so as to most easily accommodate the three potential modes of operation described above: autonomous, operator-in-the-loop and test. (Note that an operator-in-the-loop test mode will be required even for autonomous systems.) The hierarchy shown in Figure 3-2 shows a *planning authority* interacting with the planning system only at the highest level. In general, interactions may be required at any of the levels shown in Figure 3-4, especially during testing of the system. The hierarchy and its planning management functions should be designed from the outset to accommodate the expected variety of interactions and modes of operation.

3.3 Implementation Considerations

The preceding has focused on the requirements for the planning management functions. In this section we discuss important issues that must be considered when implementing the planning management functions in a hierarchical planning system.

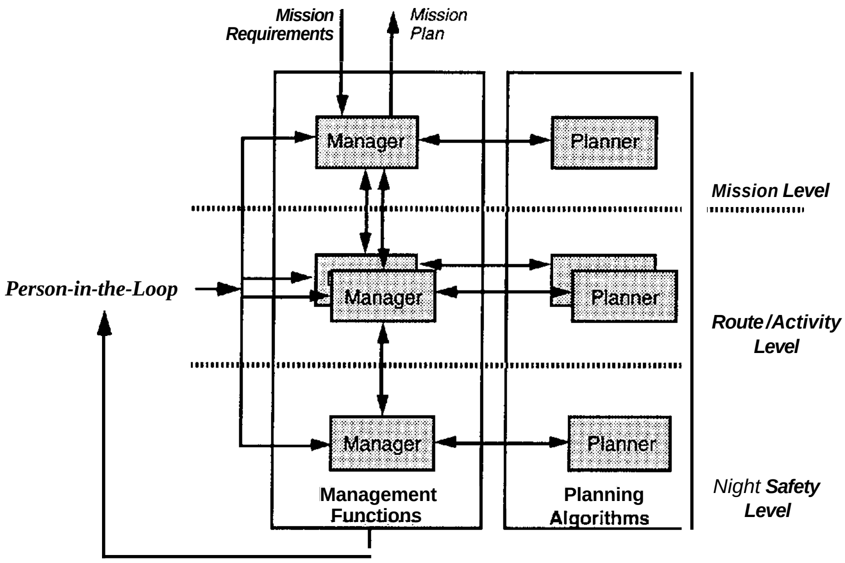

Figure 3-4. Person-in-the-Loop. The planning hierarchy can function with a person-in-the-loop by allowing the human to assume the management functions associated with a specified level of the hierarchy.

Below we describe a standardized software framework within which the planning management functions and planning algorithms at each level of the planning hierarchy can be implemented. Establishing such a framework will not only simplify the design process, but will also make it easier to expand the system design at some future time. For example, for the aircraft planning problem discussed here, we have identified a hierarchy containing two levels of trajectory planning (referred to here as high level trajectory planning and route planning). If in the future it were decided that three levels of trajectory planning were preferred, the third level could be added with much less effort if a standard framework is used for each level.

The standardized implementation described here for a particular level of the hierarchy contains three basic functions (see Figure 2-5):

- ***A Manager*** : The component which contains all of the planning management functions discussed previously.
- ***One or More Planners*** : The planners generate solutions to planning problems that are defined by the manager and/or other planners.
- ***A Manager/Planner Interface:*** This component of the framework provides a mechanism for controlling the flow of information between management functions and planning functions both within and across levels of the hierarchy.

The details of the design of the software within each component need not be identical across levels of the hierarchy. What is important is to standardize the information and control flow in and out of the components.

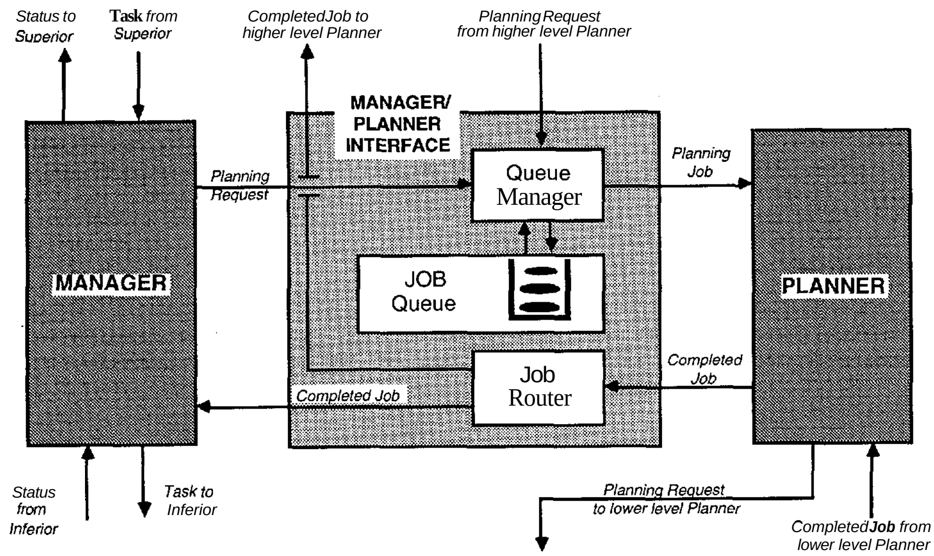

Figure 2-5. Information Flow in the Hierarchy. The manager of each level of the hierarchy generates planning tasks associated with its level. These planning tasks are packaged as jobs and sent to the planner through a queuing system. Each job contains a problem description, a priority (set by the manager), and a destination as to where the solution to the planning problem should be sent upon completion.

3.3.1 The Manager.

Consider the following example. The mission planner creates a flight plan that consists of a number of goals and associated high level trajectory segments. Prior to the execution of a new trajectory segment, the mission planning level passes the new segment to the route level manager as a task. The task includes the destination waypoint and the operational resource allocations. The route level manager directs the route planning algorithms to create a detailed route plan, to execute the route plan, monitoring the execution of that portion of the flight plan, and to replan as the situation warrants. In situations where a manager cannot produce a plan that satisfies the constraint and resources allocated by its superior, it reports back to the higher level manager. For example, if the route level manager cannot produce a satisfactory route within the specified resource allocations, it reports this situation back to the mission level manager. The mission level must reallocate the available resources to meet the current shortfall identified at the route level or reformulate the planning problem.

When the manager at a given level determines that the effectiveness of the plan that it is currently executing has been reduced or when the manager identifies an opportunity to improve the effectiveness of the current plan, the manager generates the appropriate job and sends it to the queue manager.

3.3.2 The Manager/Planner Interface.

To support the flow of information throughout the hierarchy, it is desirable to standardize the structure of that information. This can be accomplished by employing a data structure referred to here simply as a 'Sob". A *job* identifies a planning problem that some element of the hierarchy (either a manager or another planner) has defined. A job is a mechanism for packaging a planning problem into a standardized form that can be communicated throughout the hierarchy. Each job is made up of seven elements:

- ID. A unique ID that allows the hierarchy to keep track of the different jobs in the system.
- Creator. The manager or planner that created the job. This information is used by the job router to know where the results of the job should be directed when it is completed.
- Planner. The planner to which the job is to be sent. This information is required to define the destination for a job when there is

more than one planner within a level of the hierarchy.

- Priority. A value that indicates the relative importance of the job.
- Start-up Time. The time the job was created. The start-up time, together with the job's priority, is used to determine the job's location in the job queue.
- Problem Description. The complete set of inputs to the planning algorithm including objectives, constraints, resource importance factors and the time available to plan.
- Problem Solution. The place holder used to store the solution to the planning job when the planner has completed its task.
- Status. The status of the job (e.g., on the queue, executing).

Jobs are initiated by the manager. They are deposited in a job queue within the Manager/Planner Interface according to a priority and time spent in the queue. When a job reaches the top of the queue, it is executed by the planning algorithm and the results *(problem solution)* are sent back to the requesting manager or planner via the job router. At any point during the execution of a job, the manager can direct the queue manger to interrupt or terminate the job. Planning algorithms can also create jobs for planning algorithms at lower levels of the hierarchy. These jobs get handled in an identical manner although the information is passed across levels of the hierarchy. An example of a planning algorithm generating a job occurs in the mission planner. In order to determine the best ordering of the goals, the goal-point planning algorithm must know the approximate cost of flying between pairs of goals. It obtains this information by sending a job to the high level trajectory planning algorithm.

3.3.3 The Planner.

The system architecture depicted in Figure *3-2* has been developed to eliminate the need for planning algorithms to treat management issues. One concern when orchestrating the execution of the planning algorithms is the need to balance the computational load of the system so that planning is completed across all levels "just in time". Even though the management functions perform the command and control associated with the hierarchy, it is expected that in most cases, the bulk of the computational requirements will come from the planning algorithms. It is therefore particularly important that the planning algorithms be designed to perform their functions within a specified availability of the computational resources of the system. One method of achieving this goal is for the management functions to impose "time to plan" limitations on the planning algorithms during operation.

4. SUMMARY

Mission and trajectory planning problems are complex and difficult problems for a variety of reasons. First, multiple (and often conflicting) objectives must be pursued in the face of a variety of both implicit and explicit constraints. Representative mission objectives include reconnaissance, resupply, support and strike. Implicit constraints are constraints that are imposed by the vehicle design (e.g., its fuel carrying capacity, stores carrying capacity, performance envelope and subsystem capabilities). Explicit constraints are constraints that may be imposed by a higher planning authority (e.g., a required probability of survival or mission success, time or ordering constraints that may be imposed on the pursuit of specific mission objectives, navigation constraints, maneuvering constraints within the vehicle's performance envelope and constraints imposed by the time available to plan).

The fact that planning must account for significant uncertainty in the planner's knowledge of the current and future "state of the world" (i.e., the state of the vehicle and its environment) also contributes to the complexity and difficulty of the mission and trajectory planning problem. Because of this uncertainty, the formulation of detailed plans too far into the future is generally a futile exercise. As a consequence, an onboard capability to replan the mission is essential for piloted as well as autonomous vehicle applications, especially in poorly characterized environments where long endurance is required.

The requirement to replan the mission in real time adds yet another layer of complexity and difficulty to the mission and trajectory planning problem. This requirement arises not only because of the uncertainty with respect to the current and future state of the world that inevitably prevails at the time the mission is originally planned, but also because of unforeseen contingencies requiring a response in real time that arise during the execution of the mission. A higher planning authority may redefine the mission objectives or alter the constraints that are imposed on the pursuit of those objectives, the mission environment (threats, weather, etc.) might change, the vehicle might sustain failures or damage, or opportunities to accomplish additional objectives might occur.

An architecture for mission planning systems for autonomous or semi-autonomous vehicles has been described. That architecture has been described in the context of a specific planning system hierarchy designed for aircraft mission planning problems. However, the discussions here apply equally across a spectrum of space, air, land and undersea mission planning problems. A distinction has been drawn between the algorithms that create plans and the decision-making functions that control the process of creating and executing the plans: the planning management functions. A detailed discussion of the decision-making functions that comprise planning management has been presented and a standardized framework has been proposed for implementing some of the elements of the planning architecture associated with planning management.

5. REFERENCES

[1] "Mission Planning Systems for Tactical Aircraft: Interim Report," ***G.*** Hunt and T. Jones, editors, AGARD, 1991.

[2] Albus, J. S., Lumia, R., and McCain, H., "Hierarchical Control of Intelligent Machines Applied to Space Station Telerobots," IEEE Transactions on Aerospace and Electronic Systems, vol. 24, No. 5, September, 1988.

[3] Loch, J., Waller, E., Bellingham, J.G., Beaton, R. and Triantafyllou, M., "Software Development for the Autonomous Submersible Program at MIT Sea Grant and Draper Laboratory," Proceedings 6th Int. Symp. on Unmanned Untethered Submersibles Technology, 1989.

[4] Deutsch, O.L., Desai, M. and McGee, L. A., "Far-Field Mission Planning for Nap-of-the-Earth Flight", Proceedings of the American Helicopter Society Meeting, Cherry Hill NJ, Oct., 1987.

[5] Weinstein, W.W., Adams, M.B. and Hildebrant, R.R., "Traffic Flow Control System," CSDL Technical Report, The Charles Stark Draper Laboratory, Inc, June, 1988

[6] Singh, M. H. and A. Titli, Systems: Decomposition, Optimization and Control, Pergamon Press, Oxford, 1978.

[7] Tamura, H. and T. Yoshikawa, eds., Large-Scale Systems Control and Decision-Making, Marcel Dekker, New York, New York, 1990.

[8] Lasdon, L. S., Optimization Theory for Large Systems, Macmillan, New York, New York, 1970.

[9] Adams, M.B. and Beaton, R.M., "Planning and Planning Management for Autonomous and Semi-Autonomous Vehicles", AGARD Conference Proceedings No. 474, 1990

[10] Adams, **M.B.,** Deutsch, O.L., and Harrison, J.V., "A Hierarchical Planner for Intelligent Systems," Proceedings of SPIE -, The International Society for Optical Engineering, Vol 548, April 1985.

[11] Beaton, R.M., Adams, M.B., and Harrison, J.V., "Real-Time Mission and Trajectory Planning", Proceedings of the 26th IEEE Conference on Decision and Control, Los Angeles, CA, December, 1987.

Human Factors of Mission Planning Systems: Theory And Concepts

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1. SUMMARY

Human factors of advanced Mission Planning Systems (MPS) are considered from a theoretical and conceptual point of view. MPS are treated as a class of human-machine systems concerned with the functions of planning and rehearsal of mission tasks. The functions of planning and rehearsal are considered in relation to decision-making and actions in dynamic situations. Planning and rehearsal are essential for the identification and clarification of mission goals. Planning and rehearsal are cognitive tasks, involving the skills of reasoning, decision-making, visualisation and mental simulation, with associated human capabilities and limitations. Performance of these preparatory cognitive skills reduces in-flight workload, and affects the availability, quality and structure of mission-relevant knowledge. Knowledge and understanding gained during planning influences the performance of in-flight mission tasks. Perceptions of mission problems and situations are initially formulated during planning and rehearsal. Inappropriate perceptions result in inappropriate plans, reduced in-flight situational awareness, erroneous decisions and degraded mission performance. The psychology of systems design is reviewed with reference to MPS requirements. Particular attention is given to the role of automation and aiding technology in the performance of planning and rehearsal tasks. The nature of aircrew involvement in MPS decision-making is a key system design issue determining mission effectiveness. Relevant human capabilities and limitations, and the level of aircrew active involvement and machine autonomy, need to carefully considered in initial systems design. A human-systems design paradigm based on principles of adaptive aiding and co-operative functioning is proposed for advanced MPS design. The cognitive compatibility of the aircrew task and system interface is a key requirement for effective aircrew involvement in MPS processes and for successful MPS functioning.

2. INTRODUCTION

2.1. Planning and Opportunism

Adaptiveness and flexibility are key characteristics of human behaviour for survival in a changing and threatening environment. Planning enables behaviour to be purposeful. Yet planning is necessary but not sufficient for adaptive behaviour. Opportunism also is needed to provide flexibility in a dynamic environment. Contrasts sometimes can be particularly illuminating. Opportunism can be thought of as a complimentary characteristic to planning. Both are essential for adaptive behaviour.

The late Donald Broadbent spoke about planning and opportunism in his Memorial Lecture to the British Psychological Society, a year before his recent death (1). He described how most social systems, in order to cope with a changing world, need to operate at three levels, namely handling policy, conducting routine operations and responding to emergencies. At the policy level, actions need to be started to solve problems that will take time but whose solutions are not needed immediately. This is achieved by forming a model of the world and changing it heuristically to find a possible solution. Secondly, adaptive social systems need to be able to assign novel situations to a category that can be handled by a pre-planned routine. At the third "emergency" level, systems need to respond to events as they arise. This is achieved by continuously scanning the situation, and by applying appropriate condition-action rules, chosen heuristically to maximise the chances of success.

A model of how these three levels operate in an organisation responding to hazards is described in Figure 1, simplified by Broadbent from Hale and Glendon (2). In a safe organisation, it is not sufficient to have a good policy and fast reactions. There must be a procedure for dealing with abnormal conditions and hazards, where known procedures do not apply, and for which new plans must be generated.

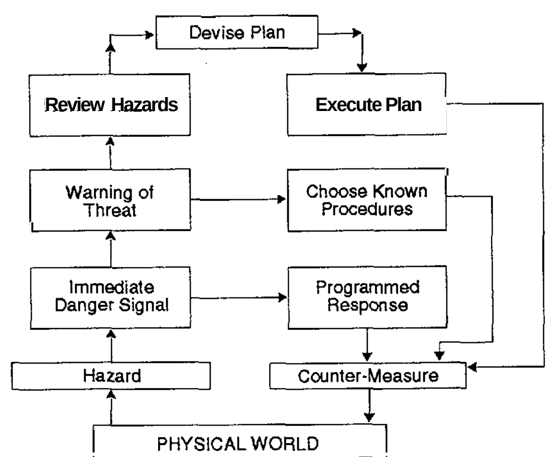

FIGURE 1- Procedures for a Safe Organisation

Broadbent identified three key features of opportunistic behaviour needed by machines to

perform symbolic manipulations and solve problems in a changing world. These key features are as follows:
(1) Travelling hopefully, i.e. try manipulations heuristically rather than attempt all possible manipulations (e.g. try the obvious first).
(2) Picking up the right language of thought, i.e. there is more than one way of representing the world legitimately (e.g. a map or a list), but the choice of representation could decide whether or not you will solve the problem.
(3) Avoiding routine, i.e. the world is rarely predictable and it is better to have a flexible set of condition-action rules rather than an invariant routine sequence.
These characteristics and levels of behaviour apply to human functions and social systems. Incorporated into machines, they allow machine systems to play games, solve logical problems and generally act intelligently.

In dynamic, changing real-world situations, particularly in warfare, performance on complex tasks and achievement of goals is influenced by a variety of both predictable and unpredictable variables and events, with associated action requirements. Planning seeks to deal with predictable events, but it can also help to cope with uncertainties, and to respond to events as they arise. A choice of pre-planned operations can be provided for dealing with emergencies and other non-routine low probability contingencies. But also by anticipation of predictable demands, and by timely "automatic" provision of the required responses, one can enable resources to be set aside to generate new procedures for responding to unexpected events and uncertain demands as they arise. A blend of committed and uncommitted resources or spare capacity is essential for dealing with the predictable and unpredictable nature of dynamic real-world situations and for maintaining closure on goals.

2.2. Objective

In the broadest sense, the prosecution of a complex military aircraft mission is similar to the performance of any human behaviour which improves with learning and practice. The intention of this paper is to consider the role and function of mission planning systems (MPS) as a class of human-machine systems with a specific purpose, namely the planning and rehearsal of mission tasks to support the skilled performance of tactical military aircraft missions. In this conceptualisation, the operator is part of the system rather than merely the system user. Furthermore, the MPS is a human-machine sub-system of the total aircrew-vehicle mission system. This view of how the system functions is based on a biological model of human functioning in terms of inputs, intemal process (e.g. decision-making) and outputs. Through psychological and cognitive theory of system functioning, it is intended to provide the framework for deriving guidance on how the design of MPS equipment should be responsive to, and take account of the needs of the system, and ultimately to exercise control over system functioning. It is proposed that an approach to MPS design developed rationally on the basis of psychological and cognitive theory of human functioning will result in MPS performance with high psychological and cognitive quality.

3. THE PROBLEM

The best** laid **schemes o` mice an' men
Gang aft a-gley.

Burns, "To a Mouse", **1786**

3.1. The Route Planning Problem

Consider the familiar problem of selecting a route by road. If both the destination of the journey, and the route to the objective are familiar, then one can set off with minimal preparation and little conscious thought to planning or rehearsal. It seems obvious where to go, and to deal with unexpected eventualities as and when they arise. Identifying way-points on the way to the objective and maintaining an awareness of progress towards the destination involves minimal effort and receives little attention. If both the objective and the route are novel, decisions need to be made about how best to undertake the task, i.e. the when and where of route planning. Identifying way-points and monitoring progress are potential problem areas. Three general strategies can be used to get to a novel objective. One might ask someone to take one there, say by following another vehicle. This *"nuplan"* strategy is similar to following a familiar route, without acquiring the knowledge. Little or no learning takes place, and if one loses sight of the leader, say due to heavy traffic, one can get into serious difficulties. Alternatively, one can ask for guidance and obtain an outline description of a known direct route. This *"provided plan"* could be take the form of a verbal account of the route changes (e.g. first left, second right.... etc.) or a rough sketch map. Thirdly, one can work out a route for oneself, with reference to a road map, and to other sources of information, such as route signs. This is the *"worked plan"* strategy.

Now consider the consequences for each of these strategies of an unexpected, but not uncommon disruption to the plan, such as a temporary diversion due to an accident, which forces one off the intended route, without sign posts to help recovery. With the *no plan* or following strategy, one doesn't know where one is, where one is going in any detail, how to get there, and one is entirely dependent on the local knowledge of the guide. The *provided* ***plan*** will have little flexibility for dealing with unexpected contingencies, other than enabling one to back-track to the start, perhaps to seek further help. However, with a *worked plan* one always knows at least approximately where one is with respect to the destination, which might have been considered in terms of a variety of altemative approaches in devising the original route. Thus one probably would be able to guess approximately the right direction, and be able to work out a revised route, either from memory or with reference to the map if necessary.

The key distinctions between the three strategies are in the processes of *goul generution,* in the clarity of *goal definition* in each case, and in the subsequent problems of monitoring and maintaining the *closure* on the goal, or *goal maintenance,* following alteration in the situation and plan disruption. The *"no plun"* strategy provides no explicit goal clarification and definition to aid recovery after disruption. The *"provided plan"* offers only a weak definition of the goal in terms of the prescribed direct route, which becomes irrelevant after the disruption. The *"worked plan"* takes time to prepare, but it provides a means of monitoring goal closure, assessing the situation and maintaining awareness of the situation along the way. It offers a flexible framework of intermediate goals for evaluating any revised routing. In conclusion, if there is a possibility of unpredictable circumstances causing a diversion from the original plan, or any other need to find an alternative route, then there will be advantages in working out the plan personally, and for actively clarifying the goal and sub-goal structure for oneself.

3.2. The Tactical Aircraft Mission Problem

Now consider the following situations on a tactical military aircraft mission:

"Leading a four aircraft, low level Simulated Attack Profile **(SAP),** over hilly terrain in marginal weather, you are bounced by a single head-on radar threat. You counter the attack, forcing you off track. The adversary manoeuvres into a visual stern attack, which again you counter until the threat is lost. In doing so, you encounter worsening weather, and in trying to avoid it you go further off track. You are then forced to make a low level abort into cloud on instruments. You then attempt to regain your original track, low-level formation and time-on-target".

Perhaps surprisingly for non-aviators, this is not an entirely unexpected occurrence in tactical operations in the European theatre. Thus, like the prescription for a safe organisation, procedures are anticipated for dealing with such abnormal conditions and hazards. This would be either through the application of an appropriate pre-planned routine, if the situation fits a recognisable category, or by heuristically applying sets of condition-action rules. In addition, in the expert pilot, underpinning the recovery strategy, typically there will be a highly developed mental model of the geographical and tactical situation, based on familiarity with the area, pre-flight map study and continuous in-flight monitoring of situational variables.

In the above example, deviations from the original flight plan were caused by changes in the airborne situation. The tactical aircraft environment can be highly dynamic. Continuous situation assessment is needed to assess the validity of pre-flight planning. Failure to monitor the situation can make planning ineffective through overly rigid adherence in a changing situation, as in the following scenario:

"On a 4-ship offensive air operation, planned for night Instrument Flying Rules (IFR), with a 40 second interval formation appropriate for night IFR defensive coverage, daylight is encountered, and the 40 second interval is continued and not reduced to maximise defensive coverage".

Plans need to be flexible in a changing world. The prosecution of a tactical military aircraft mission is a complex, four-dimensional problem-solving activity, requiring the co-ordination and integration in both time and space of diverse resources, activities, and actions, often with as many unpredictable influences and disruptions, as well as expected events. Successful performance requires extensive training and practice, supported by detailed planning and rehearsal, and the application of a combination of planning, flexibility, skill and situational awareness in the air. A balance provision is required for both a planned and flexible response which will change and adapt according to the varying complexity and predictability of the mission.

3.3. Maintaining Situational Awareness

In the 1960's and 1970's, changes in the tactical environment led to an increase in low-level flying, and geographical disorientation was a frequent problem. Together with spatial (or gravitational) disorientation, geographical disorientation became a significant source of accidents and incidents as well as a source of operational inefficiency. Subsequently, advances in automatic navigation aids, particularly moving map displays and inertial navigation systems, removed much of the navigation workload and facilitated single-seat operations. Now, with high levels of automation available for flight control and guidance, coupled with the ever increasing complexity of the aircraft missions and mission systems, the main problems for contemporary aircrew arise in managing the complex mission systems and in maintaining their *situational awareness.* Indeed, recent US statistics indicate that "loss of situational awareness" is cited as a cause factor in approximately 70% of military aircraft accidents and incidents. In current thinking, situational awareness or **SA** refers to an understanding of all the factors affecting mission performance, including the status of the aircraft and its mission system, and the tactical, spatial and geographical environment external to the aircraft. In a changing world, accurate situation assessment is the key to flexible response. SA is the "right language of thought" that provides the potential for solving in-flight mission problems.

In summary, in the airborne environment, strategies and tactics for solving mission problems are applied through a combination of planning and skill, and through the application of routine standard operating procedures and sets of condition-action rules for dealing rapidly with the unexpected. The problem of system design and training for the prosecution of tactical aircraft missions is a question of judging the appropriate balance in the provision of resources for both planned and flexible responses.

4. A FUNCTIONAL DEFINITION OF PLANNING

Plans are preparation for a specific actions, generated ahead of the time for action. Actions that are planned usually are chosen because they have predictable effects calculated to accomplish specific goals. Skilled performance requires planning. Plans are guided by strategy and tactics. Strategy and tactics are generalised forms of ideas for guiding planning in order to achieve high level meta-goals, such as maximising surprise, stealth, deception, speed, precision and defensive coverage, maintaining situational awareness, and managing workload. A plan is a formal conceptualisation of a strategy for achieving specific goals. By definition, a plan is a detailed scheme for obtaining an objective. Specifically, a plan is a prescription for the co-ordination of events and actions in time and space to achieve a specified goal. Plans provide information on the types, times, locations and performers of required actions; in other words, the what, when, where and who of planning. Execution of a plan provides information on plan performance. With a complex plan, through repeated execution or practice, information on performance can be used for the refinement of the plan in order to improve goal attainment and performance.

5. THE PSYCHOLOGY OF SYSTEMS DESIGN

5.1. Human-Centred Design

Meister (3) offers a contemporary perspective on the psychology of systems design. In this perspective, the concept of the system is an aggregate of all the elements organised in a hierarchical structure to accomplish certain goals. In human systems, such as MPS and piloted aircraft, the human is one of the critical system elements. Control of system functioning is the overriding issue in systems design. Control of functioning of human systems is determined by the interaction or dialogue between the human and the other system components.

In complex human systems, the role and functioning of the human in relation to the other system components needs to be understood, if human control of the system functionality is to be achieved and not to be weakened. Understanding of human functioning in systems can be achieved by analysing system behaviour in terms of a biological model of system functioning. This biological model comprises the system goals, with the system receiving inputs, making decisions and generating outputs to achieve the system goals. Understanding the relationship between the human and the system requires an approach to system design that considers the total system, including the human and machine components, that is both systematic and human-centred from the outset.

To preserve the appropriate human control over system functionality, a systematic human-centred approach following principles of behavioural analysis needs to be adopted from the earliest system design conceptualisation, and followed through all the stages of system development, test and evaluation. All factors that could influence design and functionality need to be considered. Behavioural analysis, design and evaluation need to be related to system goals, tasks and outputs, at all levels of system processes and performance.

5.2. Applying Human Engineering to Systems Design

The systems approach to the application of human engineering or ergonomics, summarised by Doring (4), and cited by the NATO Defence Research Group **14** on systems ergonomics (5), is shown in Figure 2. This diagram shows the links between the stages in the design and development and the information generated for the design process.

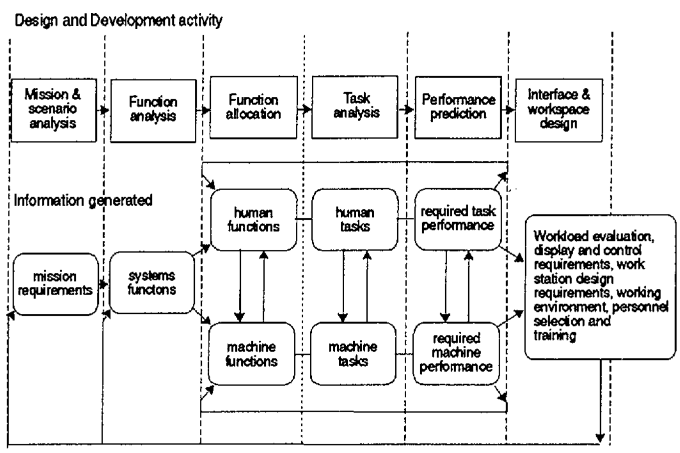

FIGURE 2- The Systems Ergonomics Approach

The sequence of stages progresses logically from mission and function analysis, function allocation, task analysis, and performance prediction to the determination of the task and interface requirements. The process should be iterative and repeared several times in the course of synthesis, analysis and design of the system.

This process is documented as a standard procedure for the application of human engineering to advanced aircrew systems design in NATO MAS Standardisation Agreement 3994 AI (6), and in equivalent National defence standards. The activities and procedures needed to meet the specific system requirement,including test and evaluation, are formalised in a *Human Engineering Programme Plan* (HEPP) that is tied to the overall system hardware and software development plan. The HEPP should be designed to identify the predictable requirements, but like any good plan, it should also contain flexible procedures and mechanisms for dealing with new problems as they arise during design, development, test and evaluation.

5.3. Human Engineering Analysis Techniques

Human-engineering methods, techniques and tools are available to assist most stages of system design, test and evaluation **(7).** They include methods for decomposing and synthesising tasks in order to predict and control attentional demands, resolve task conflicts and avoid operator overload. The applicability of these techniques is reviewed by NATO Defence Research Group 14 *(5).*

5.4. Human Resources Integration.

Logically, the capability of the system components should determine the functions assigned to them for performance. Analysis of operator capability includes measurement of aptitude, training and human engineering parameters. In conducting an analysis of potential operator capability, special emphasis is required to be placed on identifying capabilities which are unique to humans, i.e. capabilities which can not be achieved by machines. In conducting subsequent function allocation, particular attention needs to be paid to those functions which may be performed by either humans, hardware or software. Decisions resulting from these analyses ultimately lead to the definition of the tasks to be performed by the operator, the **task** loading, and the task information and control requirements. Thus, identification of areas of both unique and shared human and machine capabilities are key elements of the early system design process.

Considerable progress has been made recently in addressing the problems of integrating human resources requirements into systems procurement through initiatives, such as MANPRINT (8), and through the creation of improved human performance data bases and associated designers aids (9).

6. EVALUATING THE EFFICACY OF PLANNING

It is reasonable to assume that planning, along with training, practice, and rehearsal, improves the performance and effectiveness of complex military missions. This assumption is the cornerstone of the majority of peacetime military operations. Evaluating the validity of this assumption depends on the provision of evidence. Provision of evidence is ultimately a problem of measurement.

6.1. Measurement of Performance

Measurement of human performance is different from measurement of system perfomance. There is no general theory to link human performance measures to measures of total system perfomance. In considering this relationship, it is important to think about the mechanisms by which human performance might affect system performance. With increasing use of automation, human behaviour in advanced systems, such as MPS, is becoming more dependent on cognitive skills. But cognitive performance is inherently more difficult to measure than the performance of physical activities. Performance of cognitive activities can not be observed directly. Cognitive performance can only be inferred from the behavioural consequences and effects of cognitive activity, or from subjective reports, which are inherently unreliable. The relationship between human performance and system performance can be explored by both quantitative and qualitative measurement. The key to effective measurement is to ask the right question and to match the method to that question. Often the requirement for system evaluation must be translated from high level, abstract questions about compatibility, operability and intelligibility, to more specific purposes which suggest certain operations and measurements, such as aiming accuracy, response times and errors.

6.2. Measurement of Effectiveness

It is important from the outset to differentiate between measures of performance and measures of effectiveness. System performance measures include, without differentiating, the performance of the human subsystem. A measures of effectiveness (MOE) describes performance in relation to a performance standard, or target, in order to determine the value of the measured performance. Measures of performance less than an MOE are inadequate. A typical MOE for an MPS would be the need to be capable of supporting the planning within 30 minutes of an 8 aircraft mission in accordance with a given planning model. **A** hierarchy of MOE can be provided associated with system levels. These MOE change in nature as the system level evolves from low to high levels. High level MOE are more effectiveness oriented, e.g. median planning time. Selection of MOE should proceed from the top down. **An** effectiveness oriented MOE should be selected before determining the performance MOE on which it depends. The planning effectiveness of a new or improved MPS should be judged in terms of the difference it makes to overall mission-system effectiveness. Ideally, this should be defined in relation to a baseline performance, usually derived from an existing system, in accordance with the mission analysis requirement. A MOE should be expressed probabilistically to reflect the stochastic and non-deterministic nature of man-in-the-loop, human-system performance (e.g. 30% increased probability of mission success; 5% reduced probability of mission failure due to human error).

6.3. Definition of Mission Objectives

The generation of appropriate measures of performance and effectiveness for system evaluation depends on having a clear definition of the system performance targets. These targets are derived from an understanding of the system and mission objectives. At the most general level of description, the aim of a tactical military aircraft mission is to achieve certain operational objectives in an optimum or near optimum way. The mission is the sequence of system performances required to accomplish the goal (3). Optimisation of attack effectiveness, survivability, co-ordination and interoperability are key performance objectives of most, if not all tactical missions (10).

The key objectives translate into different operational objectives in the context of different missions. In offensive air operations, the air interdiction mission presents probably the most complex and demanding mission to perform effectively. Typically, air interdiction missions aim to achieve a multi-aircraft co-ordinated target attack, with a specific time on target,·weapons delivery sequence and attack pattern, with resolution of conflict between aircraft, terrain and weather, and with an exposure to threat over the target, and on ingress and egress, that is either eliminated, minimised or maintained within acceptable limits. These characterise the explicit goals and sub-goals of the specific tactical mission. Other implicit high-level generic goals or meta-goals common to most, if not all tactical missions include maintaining flexibility and speed of response, situational awareness, communications, and a tolerable aircrew workload. Optimising attainment of all these objectives is the skill of tactical aircraft mission performance.

Analyses of the functions and information requirements of pre-flight mission planning (11, 12) have identified a sequence of seven high level tasks, with associated sub-tasks, as comprising a typical tactical mission planning activity, namely:

1. Assimilate target and weapons data.
2. Review threat and weather data in target area.
3. Specify attack profile.
4. Optimise flight route.
5. Select aircraft configuration and procedures.
6. Review mission plan.
7. Transfer system data to aircraft.

In summary, pre-flight mission planning seeks to maximise the attainment of mission performance objectives by clarifying the objectives, analysing relevant information, making decisions, and organising actions ahead of the mission, based on predictions of situations and action requirements. The effectiveness of planning should be measured in terms of the attainment of these objectives.

7. THEORY OF BEHAVIOUR.

7.1. Behaviour Modification

DNA is the basic bio-chemical plan. It sets out the "blue-print" for the development of biological organisms. Natural selection and reproduction are sources for the modification and refinement of the DNA plan. Behaviour is more directly modifiable, but it also can have a guiding programme or plan. Indeed, planning is a fundamental component of purposive behaviour. At work, plans are an integral part of how we think about organising behaviour to achieve our goals. This seems so obvious that it is difficult to imagine that there might have been an alternative way of thinking about the organisation of behaviour.

Psychological theory of behaviour is governed by a strong desire for scientific rigour and empirical objectivity in the traditions of physical science. Accordingly, from the turn of the century, early theory presented a perspective on the organisation of behaviour which sought to avoid the postulation of unobservable, intervening cognitive control mechanisms and processes between actions and the environment. But largely through developments in cognitive psychology, the notion of a central executive controller guided by plans, became central to our understanding of the organisation of behaviour. Indeed, this is sufficiently so that theorists now have taken to explaining behaviour that is apparently not as planned, and that seems governed more by situations than by plans, e.g. opportunistic behaviour. It might prove informative to trace some of the key issues that directed early thinking to set the scene for the contemporary perspective.

7.2. Drive Theory

Early, pre-1930's theory of behaviour proposed that behaviour was ***driven*** or pushed by the biological needs and motivational state, or the state of deprivation of the organism translated into primary ***drives*** or emotions such as hunger, thirst, and fear. Understanding ***learning*** was the key issue of the time. Learning was viewed as the building of patterns of behaviour. Based on experiments with animal learning, all learnt behaviour was reduced to the development of connections of specific actions in response to specific stimuli. These connections were built up in associative stimulus-response (S-R) chains that lead to the satisfaction of drives or emotions. These S-R chains would be conditioned, re-inforced or inhibited by reward or punishment related to drives and emotions. Eventually, this explanation proved limiting in accounting for the more complex and flexible patterns of learnt behaviour produced by both animals and humans.

7.3. Theory of Purposive Behaviour

Evidence for the contrary notion that behaviour was planned or *purposive* rather than driven was first provided by by Tolman (13) in the 1930's from experimental studies of maze-learning in rats. Purposive behaviour strives towards *goals.* Purposive behaviour is governed by goals or *goal-driven,* in an apparently teleological manner, rather than being driven or pushed by motives and states of deprivation. Unlike S-R or drive theory, this explanation assumes some internal representation of the goal, the purpose and the plan. When familiar paths in a maze were blocked, rather than learn an entirely new route, the rats were able to orient themselves towards the direction of the reward or goal, and to quickly find a revised solution. These studies suggested that the rats built up an internalised representation or *cognitive map* of their environment, with some central executive mechanism having a flexible, goal-oriented programme or plan for the control behaviour, rather than just a simple associative chain of responses to the immediate stimulus (12).

Soon after, Hebb (14) and Lashley (15) described the cerebral mechanisms required for the high level co-ordination and integration of actions. This went beyond the notion of associative chains of reactions, to speculate on neurological systems necessary for the memory and co-ordination of spatial and temporal order. The notion that advanced biological organisms more often learn guiding principles, programmes and plans rather than specific responses was advanced further by analogy with a computer programme designed for guiding behaviour in a flexible way (16). Learning then could be conceived as involving the development of *hierarchy* of behavioural units, each guided by plan, which at the lowest level, with over learning, could operate automatically, rather like instincts or habits, without focal attention.

The ability to acquire an almost unlimited variety of guiding programmes or plans is the basis for the flexibility and adaptability that characterises human behaviour. These developments in understanding of the organisation of behaviour provided the foundations for contemporary cognitive science.

7.4. Control Theory: Skill and Feedback

In the late 1940's, psychologists sought to determine how levels of performance on complex tasks such as the tracking ***skill*** involved in following a target and flying could be improved by training. Skill is ability acquired by training. Skill is purposive. It has a goal. Military and industrial research on the acquisition of human psycho-motor skills brought further understanding of the role of plans and specifically on the importance of *feedback* in purposive behaviour.

Analysis of tracking skill led Craik (17) to propose a formulation taken from control engineering that described the skilled performer **as** a *"closed-loop negative feedback"* system. He suggested that during skilled behaviour, man functions as a closed-loop control system, in the manner of a servo-mechanism with corrective feedback. The concept of feedback, borrowed from control engineering, denotes the output from the system that is fed back into the system. Feedback tells the system what it is doing. Because behaviour is not performed in a vacuum, in all systems there will be some form of *disturbance* or *noise* which will introduce a discrepancy between the actual and the desired system outputs. With purposive behaviour, it is reasonable to assume that there is some stored internal representation of the desired output, in the form of an intended action, expectation or goal. Through a comparison of the actual output with the desired output, negative feedback indicates what is wrong, and the subsequent error signal provides the basis for correction and *compensation* and ultimately control, flexibility and self-regulation.

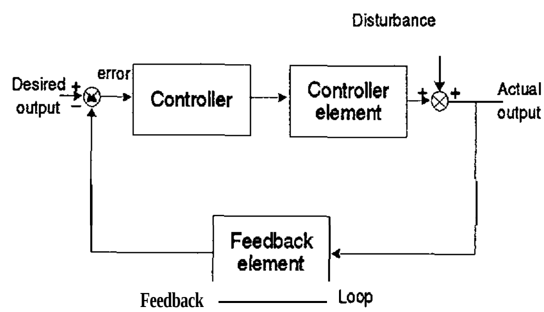

FIGURE 3- Closed Loop Negative Feedback System

The S-R formalism proposed earlier emphasises *reinforcement,* whereas the feedback/control formalism emphasises *information.* S-R does not involve feedback, since the input calls for a specific response, and the response is either right or wrong, but not modifiable. Thus, the **S-R** approach can be regarded as an *"open-loop"* system

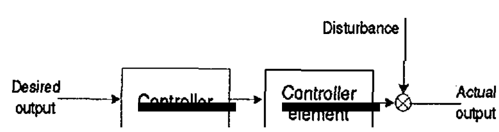

FIGURE 4- Open Loop S-R System

Through the closed-loop negative feedback formalism, complex skills may be conceived of as not having a well-defined stimulus or response, but rather as having a goal to strive towards. In this way, *closure* on the goal, through reduction of the mismatch between the actual and desired output, becomes the important characteristic of skilled behaviour, rather than the actual behaviour used to achieve the goal. A characteristic of the skilled performer is appearing to have a seemingly unlimited repertoire of behaviours that enables goals to be achieved despite unexpected disturbances.

8. THEORY OF COGNITION

8.1. Prediction and Models of Performance

The performance of skills is more than a passive process of compensation for present or past error signals. By getting ahead of the input, by organising and effectively controlling its nature, skilled performance goes beyond passive compensation to operate on the basis of ***predictio.*** Prediction is a characteristic of planning, in the sense that both are concerned with future states. Evidence of predictive behaviour in the performance of skills suggests that the human operator naturally strives to control the future state of the system. This seems to be achieved by building up an internal representation or *model* of the temporal and spatial properties of the input that can be used to generate the required output ahead of the input. This ***predictive model*** must provide a representation of the world that can be manipulated faster than real time. This can be used to compensate for reaction time or transmission delay. In modern control theory, additional computational elements (Kalman filter, optimal controller) are assumed to reside inside the control loop for the purpose of generating an internal model and for prediction (18).

Performing according to predictions implies that open loop control or *automatic* performance is employed when the internal predictive model of the environment indicates certainty about what is about to happen, and that it is possible to respond in advance. In this way, skills become habits. Problems arise if the model and the assumption of certainty are not valid. Then skills can become bad habits. The ability to form valid models of the situation, to use them for prediction, and to go between closed loop and open loop behaviour as required, is efficient for processing, but more importantly it is a typically adaptive characteristic of human behaviour.

Contemporary theory of human information processing, supported by a wealth of evidence, assumes that the resources available for attentional processes, including the working memory, are limited in terms of capacity and processing rate. Thus, breakdown in performance in complex, dynamic situations often is attributed to task overload, where the demand for processing from the environment exceeds the supply of attentional resources. Automatic performance is assumed to make minimal demands on attentional resources. It is adaptive in that it frees limited central processes for other tasks.

8.2. Theory of Cognitive Skills

Definition of goals, feedback on performance, and prediction of performance demands based on an internal predictive model of the environment, are fundamental concepts and principles of behaviour that is skilled, planned and purposive. Thus far, the discussion of the theory of skills has been restricted to psycho- or sensor-motor performance. But the ability to choose an appropriate internal model of a situation for prediction of demands is a ***cognitive skill*** rather than psychomotor skill. Prediction can be thought of as a process of generating ***hypotheses*** or ***inferencing*** about situations, based on incomplete data, such as predicting hostile intent, leading to ***expectations*** about future events. Since the future is largely uncertain, expert prediction is likely to involve processes for the generation of multiple hypotheses about likely future states with differing degrees of ***plausibility.*** This involves processes for seeking relevant data and for the testing and acceptance, rejection or modification of hypotheses, predictions and expectations.

In one theoretical formulation, known as ***perceptual control*** theory, all behaviour is conceived as being directed to the control of perceptions at a variety of levels of abstraction simultaneously (19). **A** hierarchy of control systems is postulated that maintains percepts at desired levels in accordance with goals, by means of actions and feedback on performance on the outer world. Actions are normally taken to make perception closer to some desired state. Thus, behaviour controls perception. Figure 5 illustrates the basic control system concept. In this system, the perceptual input is compared with a desired or reference percept, and the system outputs the the difference as an error signal that causes effects to happen in the world. Neisser (20) proposes a theory of the ***perceptual cycle*** that has similar characteristics for dealing with the interaction between the perceiver and the environment. In this formulation, ***knowledge*** in the form of mental models, or ***schema,*** leads to anticipation of certain kinds of information, and directs attention and exploration to particular aspects of information in the environment. The perceiver picks up or samples from the available information, and this in turn modifies, or updates, what is known about the world in general.

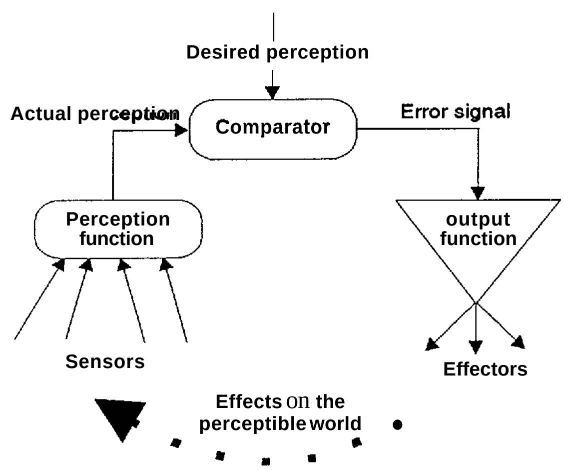

FIGURE *5-* The Basic Perceptual Control System

Cognitive skills differ from psychomotor skills in that they involve ***symbolic processes*** and the acquisition and manipulation of ***knowledge*** in the form of goals, understanding and ideas. Optimising the attainment of all mission goals is the cognitive skill of mission performance. The planning and prosecution of a tactical military aircraft mission is essentially a problem-solving exercise, with cognitive and psychomotor skill components, involving judgement of the cost-benefits and risks, and the co-ordination of spatial and temporal objectives. Whereas all skills can be said to have a problem-solving character, problem-solving is the basic mode of cognition, and problem solving is the principal objective of cognitive skills. Evidence indicates that the basic control architecture for cognitive skills is ***hierarchical, goal-structured*** and organised for problem solving. Highly complex cognitive skills, requiring optimisation of attainment of multiple goals, are likely to be controlled by ***heterurchicul*** rather than by hierarchical goal structures.

8.3. Knowledge Acquisition

Stages in the acquisition of cognitive skills can be identified in relation to the manipulation of knowledge. Evidence indicates that as cognitive skills evolve, information or ***declarative knowledge*** about the skill is rehearsed and compiled into an increasingly refined procedural form, and then applied more appropriately, with concomitant increases in speed of performance (21). ***Knowledge of results*** from the performance of cognitive skills can be thought of as serving the function of feedback in sensor-motor control processes, except that the provision of knowledge of results on cognitive skills may not be as continuous and immediate as the monitoring of sensor-motor control output. Thus, learning, compensation, and prediction of cognitive skills may not be smoothly and rapidly achieved as in tracking skill. On the other hand, the feedback on cognitive skills can more symbolic and abstract, and thereby more compatible with the kinds of information needed in measures of system performance and system effectiveness, such as probability of mission success.

Mission planning is concerned particularly with ***spatial knowledge.*** Thorndike & Hayes-Roth *(22)* showed that different forms of spatial knowledge serve different task functions. Spatial knowledge can be in the form of ***route knowledge*** or ***survey knowledge.*** Koute knowledge is typically derived from experience. It involves a sequential record of the space between various landmarks and features in the environment, represented in an ego-centred frame of reference. Survey knowledge, on the other hand, has a world-centred frame of reference, and involves the topographic properties of the environment in a fixed co-ordinate system. Route knowledge serves to identify landmarks and features, whereas survey knowledge is used to estimate distances and relative directions.

9. THEORY OF MEMORY

9.1. Schema

Theory of memory makes distinctions between the kinds of memory necessary to support on-going tasks, namely working memory, and the nature of long term memory storage. ***An*** issue of major theoretical significance concerns the kinds of storage mechanisms needed to account for the acquisition of skills. What is the nature of the intemal representation of desired outputs, predictive models, knowledge of goals, expectations and ideas? How is it structured and what are its defaults and constraints? Mechanisms for the retention of skills need to account for the characteristic flexibility and generalisability of skills, and the apparently infinite variety of skilled behaviour that seems to be produced from a finite action experience. ***An*** infinitely expandable store of behavioural units would be insufficient, as well as an inefficient and unrealistic mechanism. The concept of ***schema memory,*** originally proposed by Bartlett (23) for understanding memory for discourse, provides a plausible explanation of how flexibility and generalisability can be economically achieved in memory storage. Bartlett noted that in remembering stories, people often tend to have poor recollection of the story details, but that they still seem to be able to recall the gist of the story. Similar findings have been reported in recent research on the structure of autobiographical memory. This suggests a form of generalised memory or ***schemata.*** Schemata are generalised abstractions, or packets of knowledge, depicting different kinds of situations, not in detail or at the surface level, but containing the gist of the essential meaning, or of what it is important to remember. Schemata comprise the key abstract features or relationships that characterise the important differences between situations. They could be described as culturally stereotyped knowledge. The kinds of errors of recall in discourse include the omission of details, but also ***errors of*** *commission.* Bartlett noted that when memory for details was particularly weak, embellishments were often added, which while not part of the original story, nevertheless were plausible, meaningful and coherent in the story context. It seems that what is recalled is what is understood, and that the mechanisms of memory are keyed to the processes of ***comprehension*** and ***understanding.***

In accordance with the schema theory formulation of memory storage, experience, practice and rehearsal, involving variable instances of the schema, all function to strengthen the abstract representation of the general prototype or class of schema. Through this strengthening, the schema becomes impervious to decay and more permanently stored, and it becomes more flexible and generative in the actions it produces.

In skill acquisition, the general schema selected is modified and refined to produce the instance required to solve the problem. This could be by providing a plan or cognitive strategy, by matching the specific task demands, and or by exercising the degree of precise control required to achieve the task goals. Errors and mistakes are used to develop schemata and to refine specific schema instances for improved understanding of situations and to generate more appropriate plans. Strategies and tactics for problem-solving may be considered to be general schema, whereas plans are specific schema instances.

9.2. Scripts and Frames

A further useful form of memory packaging of knowledge, particularly relevant to MPS, concerns memory for distinctive sequences of events or sequence stereotypes. It seems likely that some knowledge is organised into structures comprising a stereotyped order of events or a ***script*** (24). In this idea, fragments of a sequence can serve to retrieve from memory and activate knowledge of an appropriate script. This script can be used to fill out details necessary to understand what has taken place, to make predictions and to guide behaviour. Schema for events that are normally put together in a rule-defined structure, with a normal sequence, such **as** story schema, can be described as a general class of structures called ***frames,*** containing narrative, objects and scenes. Schema theory, coupled with the theory of limited attentional resources and working memory, has been proposed to account for the processes of situation assessment and situation awareness. Figure 6 presents a recent conceptualisation by Endsley (25) of the system of relationships between actions, the environment, the mental model of the situation, and goals, plans and scripts. In this representation, goals are conceived as the ideal state; plans are the projected state; and scripts are the outcome that guide action.

Schemata, scripts and frames seem particularly appropriate concepts for the storage of knowledge for ***routine*** problem-solving where pre-formed sets of procedures are appropriate. Generic plans and templates are used to provide solutions to routine planning problems, based on doctrinal constraints on the types, times, locations and performers of events. These include the use of waypoints, standard initial points (IPs), default speeds, fuel and timing calculations, standard tums, formations, gates, attack profiles, corridors, reporting points and recovery procedures. They are all examples of pre-formed set procedures that have the characteristics of schema, scripts and frames. It seems likely that the many routine aspects of mission planning can be thought of in this way. But other procedures will be necessary for thinking about non-routine situations or ***creative*** problem solving, where no script or similar schema structure **is** appropriate. The application of general ***rules of inference,*** such as "if, then" reasoning, for deducing understanding without scripts seems likely to be used in less stereotyped situations.

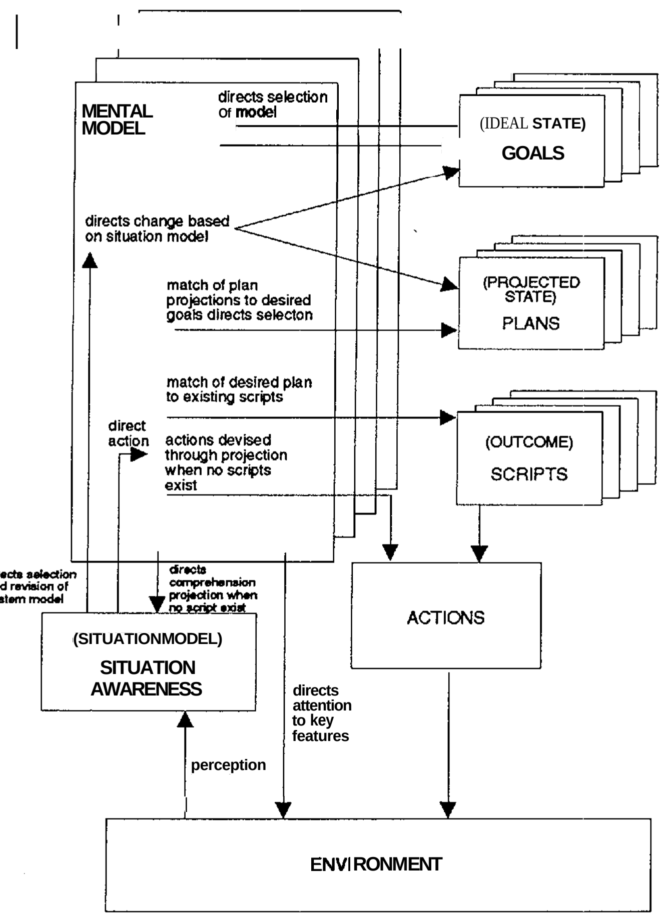

FIGURE *6* - Model of Situation Awareness in Dynamic Decision Making

9.3. Limitations of Schema Memory

Schemata are activated by data from the environment in recognising the meaning of situations. They provide predictions and hypotheses about situations when the data is incomplete, uncertain or ambiguous. They control and guide behaviour by encoding the goals, expectations, intentions and desired system outputs. Schemata account well for flexibility and generalisability in organising memory, and for ultimately guiding adaptive behaviour. However, the weakness of the schemata concept for behaviour is that the organism may tend to accept inputs that fit existing schemata, known as ***confirmation bias.*** Ambiguous inputs will be interpreted as supporting existing schemata, known as ***belief bias,*** and inputs will be rejected that are seem implausible and inconsistent with past experience, leading to *unconflicted* ***adherence*** to the original schemata. There is considerable evidence from behaviour that it is much easier to accept new knowledge which fits the existing model, than to use new knowledge which does not fit.

This fact of life is particularly relevant to consideration of the *validity* of training, practice, planning and rehearsal. Building an inappropriate model of the situation and executing an inappropriate plan can have serious consequences for dealing with real situations.

10. THEORY OF HUMAN ERROR

10.1. Systematic and Random Error

In human-machine systems, errors can arise from *variability* in either human or system performance. Variability is an inherent characteristic of human performance that allows learning and adaptation. However, prevention and prediction of errors is an important function of human-machine systems design. Errors can be either systematic or random. By definition, systematic errors are predictable and therefore they are potentially preventable or avoidable by design. Alternatively, the negative consequences of systematic errors can be anticipated and minimised. For these reasons it is more useful to regard errors as instances of human-machine and human-task mismatches that can be rectified or minimised by design. **MYS** must permit operator variability, and support learning and adaptation whilst at the same time tolerating errors. Systems intended to support exploratory problem-solving, with a practice and rehearsal training function, will require an *error-tolerant* system design.

10.2. Skill, Rule and Knowledge-Based Error

Analyses of the kinds of systematic errors that humans make in real world situations suggest a functional model for human decision-making during problem-solving based on three levels (26). At the *skilled-bused* level, during the performance of sensory-motor tasks, immediate skilled responses are provided to routine practised situations, without conscious control as smooth, automated, integrated patterns of behaviour. Performance at this level can be said to be "data-driven". Errors at this level are unintended failures of skill, due to slips or lapses of attention. At the *rule-based* level, responses are provided to novel situations capable of being fitted into categories of situations based on past experience and training. This can be achieved by assessing the situation continuously, and by applying a set of condition-action rules, which specify what action is appropriate in an instantaneous situation to maximise the chances of success. Errors at this level are incorrect applications of rules, misperceptions of evidence and misclassifications of the situation. At the *symbolic* or *knowledge-based* level, equivalent to the creative problem solving referred to earlier, pre-established problem solutions are inappropriate and totally new problems require entirely new procedures and solutions. These can be derived slowly by forming a model of the world and changing it heuristically. Figure 7 shows the relationship between these three levels of control.

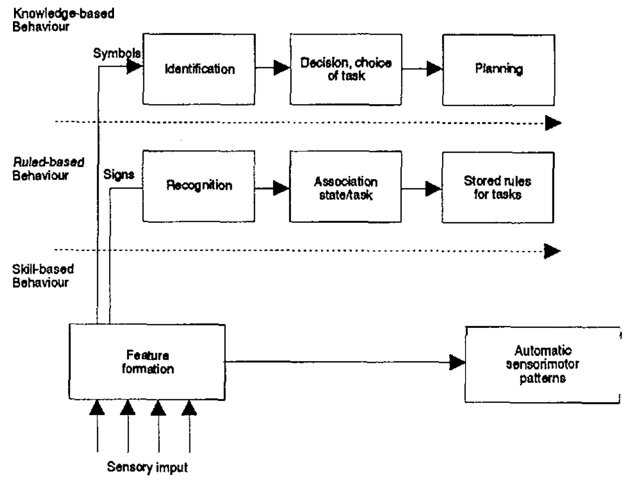

FIGURE 7 - Three Levels of Control of Human Actions

Performance at the two highest levels can be considered as "rule-" or "model-driven". Errors at the knowledge-based level are more variable in form, arising for example from confirmation bias, bounded rationality, and an incomplete or inaccurate knowledge base. They include errors of reasoning and mistakes where the action is intentional but incorrectly chosen based on incorrect knowledge, slips of memory or high workload. Another category of knowledge-based behavioural error is when actions are consistent with intentions but where the sub-goals of the intentions are not acceptable in terms of mission performance objectives, such as when testing a false hypothesis makes the overall problem worse.

In this formulation of skills, rules and knowledge (or **SRK** paradigm), during the acquisition of skill the control of behaviour develops from being govemed by individual specific cues and rules, to those of a more global nature, related to the patterns of activity rather than the acts. The intentions become expressed in terms of the goals rather than the acts to perform. The task becomes automated and performed without conscious awareness, unless unexpected deviations occur.

10.3. Error Recovery

The ability to recover from errors depends on the observability and reversability of the unacceptable consequences and effects of errors. The observability of errors will depend on the perceptability of the mismatch between the expected and actual responses to system inputs. The reversability of errors will depend on the availability of alternative system control patterns or strategies (27).

At the skill-based level, such as flight path control, tnismatches need to occur for fine tuning and optimal adjustment of schemata to the temporal and spatial characteristics of the mission environment. Simulation of flight is obviously the safest environment for flight control learning to occur. At the rule-based level, the development of rules-of-thumb and "know-how" requires refinement through experimentation, preferably in **a** safe simulation environment. So does identification of the appropriate situations and conditions for applying the rules. The completeness and quality of the representation of the mission situation in the simulation environment will be **a** major determinant of the situation assessment and classification. At the knowledge-based level, working with totally novel problems and unfamiliar situations, by definition it will be impossible to establish the complete set of conditions pertaining in the real-world. Inevitably, feedback and prediction from MPS operations never will be always completely valid. MPS tools in support of analysis, evaluation, reasoning and planning should serve to reduce error in knowledge-based behaviour.

11. THEORY OF DECISION MAKING

11.1. Situation Assessment

In the SRK formulation, attention is drawn to the importance of *situation assessment* in decision making. Situation assessment concerns the quality of the internal model of the situation and the appropriateness of the activated knowledge schemata. he-flight situation assessment is a basic MPS function. It is supported by information obtained from the MPS digital database, maps, reconnaissance imagery and intelligence information and estimates of hostile intent. The rate of change of situation assessment information will vary according to the type of situation and data. The currency of the situation assessment has a major bearing on the effectiveness of planning and on the quality of MPS performance. In **a** highly dynamic situation, situation assessment is an ongoing activity requiring frequent and continuous updating, both during pre-flight and in-flight mission management. In both cases, poor situation assessment leads to loss of situational awareness in flight, which can have serious consequences for the achievement of the key mission goals of attack effectiveness, survivability, co-ordination and interpretability.

Situation assessment is a key determinant of errors and performance in human problem-solving. Misperceptions of evidence and rnisclassifications of problems and situations are common sources of errors involving the incorrect application of rules. Activation of the appropriate schema and script identifies which set of condition-action rules apply. Understanding the situation can be thought of as the *mapping* or *cognitive cnmputibility* between the situation data and the relevant background knowledge stored as schemata in memory. The degree of richness of the mapping or compatibility could equate to the strength of the feeling of familiarity.

11.2. Recognition-Primed Decision-Making

Situation data are needed to generate a model of an entirely new situation to which existing rules do not apply. An aircrew maxim for response when confronted with an entirely novel emergency situation is "whatever you do, do something". Observations of naturalistic decision-making and actions performed in emergencies, such as during fire-fighting, have emphasised the key role of situation assessment in problem-solving by experts, particularly when under time pressure. Evidence has accumulated that decisions and actions taken by experts during complex problem-solving seem to be driven or *primed* by the perception of the category or the type of the situation as experienced in the past, or by the situation schemata that most closely characterise or have the best mapping with the present situation. The following description is thought to characterise the kind of decision making mode commonly used by experienced people: "The last time a saw this type of situation, I took this action. It worked well, so I'm going to do it again". The initial goal is the effect it had last time. This process has become known as "*recognition-primed decision-making"* or RPD *(28)*. Some amount of mental simulation may take place to perform abstract testing of particularly uncertain elements of the plan. But generally, action is initiated rapidly, the effects are monitored in real time, and the plan is altered according to the perceived changes in the recognised situation.

11.3. Analytical Decision-Making

RPD represents **a** natural strategy for making decisions when the time available is insufficient for a systematic, logical analysis of **a** problem and all the potential solutions. It provides a cognitive revival of the S-R concept in terms of leamt condition-action rules for dealing with novel situations under time pressure. The more traditional, systematic approach to decision making involves the detailed identification, weighting and evaluation of decision options and action alternatives. These different approaches should be considered more as the ends of a dimension of decision making strategies, with scope for blending of the two tnethods according to the circumstances, rather than as two mutually exclusive alternatives.

There is mixed evidence conceming the relative efficacy of the RPD and analytical decision making strategies. Experts will be able to employ the RPD strategy more successfully than novices because of their richer experience base and the availability of more appropriate schemata. Novices will need to employ an analytical strategy while building up knowledge and schemata to support an RPD strategy. Experts also will need to revert to more analytical strategy when forced to operate at the knowledge-based level because previous experience and condition-action rules do not apply, when dealing with totally new problems requiring totally new solutions.

12. THEORY OF MENTAL TRAINING

12.1. Visualisation

An important function of mission planning is to provide an opportunity for ***mental practice*** of the task. During mental practice, the aircrew activate mission knowledge, and imagine, visualise and mentally rehearse performance of the mission. Evidence for the reality of mental imagination and visualisation comes from tests of the spatial and temporal manipulation of imaginary objects (29, 30). When required to make decisions about the similarity between different two dimensional drawings of the same three dimensional object, decision times were an identical linear function of the angular difference in the portrayed objects. This suggests that the observer performs a mental process equivalent to the physical rotation of the object, until their orientations match. Other evidence for the existence of visualisation and mental rotation comes from experimental studies of map reading with perspective and plan view maps (31). When required to make decisions about the similarity between plan and 3-D perspective views of schematic maps, decision times were a linear function of the angular disparity of the images.

People spontaneously imagine objects that they expect to see. There is substantial evidence that when an observer expects to see an object then the speed and accuracy with which the object can be detected or identified are improved. Visualisation of objects can be thought of as providing a ***visual priming*** to aid subsequent perceptual judgements. MPS 3-D visualisation facilities which simulate the appearance of route and target imagery may serve to facilitate perceptual judgements in flight, as well as supporting planning decision-making. The problem is that facilitation occurs only when the imagined and observed objects are similar. **If** the imagined and observed objects differ, then visualisation may produce interference and performance will be degraded. Therefore, it is probably important that the images of the terrain surface and surface objects presented on MPS should be as realistic as possible to aid visual priming in flight. Inaccurate, low fidelity or highly artificial symbolic representations are likely to interfere with the generation of appropriate mental imagery and they could be potentially misleading in-flight. Care must be taken in both how the images are designed and in how they are intended to be used.

Evidence from studies of training indicates that the benefits of mental practice tend to be less than actual physical practice (32). But it seems that mental practice helps with the learning of the symbolic and strategic components of tasks, but not with the actual production of the actions, which requires physical practice (33). This implies that the stronger the symbolic nature of the task, the more likely mental practice will facilitate learning. For this reason, mental practice is likely to be particularly beneficial for the performance of cognitive skills.

12.2. Schemata Refinement

Mental rehearsal and visualisation of mission performance can be thought of as processes for the activation and refinement of mission schemata. Cognitive maps can be regarded as orienting schemata **(34).** The canonical form or "most favoured" natural mental map representation for many planning tasks is a north-up plan view. Planning is traditionally performed on paper maps in this orientation. But for an aircraft pilot in-flight, the ego-centric judgements of spatial location that are required for flight path control decisions favour a canonical orientation that is forward and track-up i.e. a perspective map. **A** perspective cognitive map with a track-up orientation has less angular disparity with features in the real world than obtained with a north-up plan cognitive view. Consequently, one of the main aircrew cognitive tasks performed during map study and mission rehearsal is to imagine the mission being performed through a cognitive map with the view rotated from a plan to a forward perspective. Imagining the mission situation and the sequence of tasks during planning provides a symbolic environment for evaluating, manipulating and refining decision and action sequences, for clarifying intentions and expectations, and for strengthening the schemata that eventually will be used to guide behaviour in-flight.

3-D perspective map formats are proposed for both pre-flight **MPS** and for in-flight cockpit displays for situation assessment. But the effectiveness of such 3-D visualisation tools for mission planning needs to be judged not just by how readily they present recognisable perspective images for situation assessment and route evaluation, but also by the quality of cognitive schemata that are generated by them and the availability of the resultant schemata for use in flight. Imagining the mission and actively constructing orientation schemata from a traditional plan map view is demanding and time consuming. But it is not known if working from a perspective view necessarily leads to more durable and useful knowledge schemata in flight. It is conceivable that MPS could provide levels of aiding and automatic routing, with such little requirement for active involvement in visualisation **as** to render the plan as ineffective as the "provided plan" referred to earlier. Visualisation aids should support rather than replace the need for mental preparation and training.

13. THEORY OF HUMAN INTERFACE DESIGN

13.1. Human-Computer Interaction

There is a lack of general theory for solving the problem of human-machine interface design. In the field of human-computer interaction (HCI), concepts from control theory have exerted some influence through theories of perceptual control (19, 20). Perceptual control theory concerns interaction with the environment in the broadest sense. HCI models tend to focus on human interaction with machines (computers) rather than on the way in which human-machine systems interact with the environment. As a result, assessments of the effectiveness of HCI design tend to be limited to generic considerations, such as useability and compatibility, rather than MOE changes in specific human-system performance variables. The GOMS model proposed by Card et al (35) analyses the cycle of activities in human-computer interaction from goals to selections, through operators and methods. A theory of action is proposed by Norman (36), in which discrepancies between the psychological variables, expressed as goals and intentions, and the physical variables, in the form of the systems mechanisms and states, are the major interface design issues. The discrepancies to be resolved are referred to as the *Gulf of Execution* and the *Gulf of Evaluation*. The gulf of execution concerns the gap from the goals to the physical system, including intention formation, specifying the action sequence, executing the action, making contact with the input mechanism of the interface. The gulf of evaluation concerns the gap from the physical system to the goals in comparing the interpretation of the system state with the original goals and intentions (including perception, interpretation, and evaluation), i.e. the feedback loop. Evaluation takes place at different levels of intention and action which can be thought of in terms of the skill, rule and knowledge-based (SKR) formulation.

The notion of levels of evaluation is a feature of the theory of *layered protocols* developed by Taylor (37), based on perceptual control theory. Initially proposed as a general theory of communication, layered protocols theory is used to account for the mechanisms of human-computer dialogue in terms of a hierarchy of control-feedback loops, at a number of levels of abstraction, with some independence of perception and action between the "dialogue partners" or intelligent entities. The basic control system is shown in Figure 5. These elementary control systems are conceived as connected in a hierarchy in which perceptual systems of lower level control systems combine to provide the sensory inputs to higher levels.

13.2. Manual Control Paradigm

Aircrew interface design has generally evolved on a pragmatic basis, without any guiding theory. In retrospect, three general paradigms can be identified that have been used to solve the problem of aircrew interface design **(38).** Traditional cockpit interface design has been guided by the *manual control paradigm.* In early aircraft, manual control was the only option for achieving safe take-off and landing, and for maintaining stable directional flight. The design of the pilot interface was primarily a problem of providing a closed-loop negative feedback control system with the pilot as the adaptive element, as in the feedback and skill formalism used to account for the acquisition of tracking skills. Manual control with negative feedback is the basic paradigm for traditional "worked plan" paper and pencil methods for route planning and map preparation, and techniques for in-flight map reading and navigation guidance without sophisticated aids. Contemporary **MPS** interfaces employ continuous manual control, with closed-loop negative (mostly visual) feedback, using mouse, roll-ball and stick devices, for pointing and moving functions and for graphical input and spatial manipulation. Discrete manual control, with tactile, visual and some auditory feedback on performance, is provided for data entry functions by keyboard and push-button controls. It is conceivable that, with the mission simulation and rehearsal capability afforded by advanced **MPS,** perhaps linked to flight simulation facilities, continuous manual control could be used to prototype, simulate and refine aircraft flight control manoeuvres, and perhaps even to specify manoeuvres for automatic control in flight.

13.3. Supervisory Control Paradigm

Since the 1940's, advances in technology have increased aircraft capability, systems complexity and the number of sub-system control tasks. Consequently, many aircraft operations now must be carried out under automatic control in order to avoid unacceptable aircrew workload. The development of **MPS** reflects this trend to automate functions that reduce aircrew workload. In addition to the need to contain pilot workload, transferring tasks and functions from humans to machines is the logical result of exercising the division of labour in human-machine systems on the basis of the relative advantages of humans and machines. Tasks and functions will be allocated to machines if machines are able to perform them better and more cost effectively.

Thus, many operations, previously controlled manually by humans, are now controlled by machines, with the human relegated to the role of monitoring task performance, or as a back-up in case of equipment malfunction or failure. This transfer of functionality to automation has led to the design of human interfaces for monitoring automation performance that can be described as being guided by the *supervisory control paradigm* for interface design. **MPS** interfaces can be conceived as employing a supervisory paradigm in the interface design for planning functions carried out automatically by the system, with aircrew monitoring of performance and outputs. Examples of candidate functions for MPS automation include fuel and timing calculations, and threat avoidance routings in the most advanced systems.

The concept of supervisory control describes a solution to man-machine system design where the primary tasks of humans are to monitor the functioning of the system, and to detect, diagnose and correct system malfunctions. In this formulation, the human is essentially outside the active control loop, leaving normal routine system control to automatic processes, whilst retaining the power to intervene with manual control, if necessary. The concept is equivalent to the open-loop (no feed-back) **S-R** system for automatic skill performance, with technology rather than the human responsible for the automatic performance, and with the human intervening *to* provide the feedback loop when performance fails. The human is elevated to the status of system manager, with the flexibility to determine function allocation and to delegate tasks for autonomous machine operation (39).

The main problem with this interface design paradigm arises from the unreliable nature of human monitoring performance, or the problem of closing the "gulf of evaluation" without an active feedback loop. Just as an invalid predictive model can insidiously cause automatic skills to become bad habits, the performance automation technology can become degraded without attracting attention. Attention or *vigilance* is difficult to sustain on tasks that require only infrequent and occasional human involvement in information processing, decision making and action. Egglestone (37) identified three interface design problems with the supervisory control model. Firstly, humans are not reliable monitors and experience difficulty maintaining alertness and vigilance over time without active involvement in the systems operation. Secondly, faults and malfunctions, and their causes, are difficult to communicate *to* a supervisor outside the active control loop. Thirdly, rapid human intervention in an emergency is difficult to achieve when normally outside the control loop because the pilot will have a poorly developed mental model of system functioning. The military flight environment requires rapid decisions and short response times. The supervisory control model is not optimised for operating in highly dynamic environments. These problems become particularly apparent in tasks requiring sustained performance over long periods of time. But they can also cause difficulties in tasks that are performed routinely, with infrequent variation in system performance, and consequently low expectations for the need for human intervention.

The supervisory control paradigm has relevance to **MPS** with regard *to* the design of the interaction between the planner and automatic planning functions. Problems can be expected to arise in supervising automatic MPS functions from undetected degradation of system performance and from reduced human intervention capability. In addition, caution needs to be exercised in the automation of critical functions which depend upon human judgement for performance evaluation, such as situation assessment and route generation for threat avoidance. Being outside the control loop for these important functions will make it difficult to exercise performance evaluation during planning, and it may make it difficult to develop an appropriate mental model of the proposed solution for activation in flight. The risk is that the necessary schema for flight will not be activated or refined, and little or no learning will take place, as in the "no plan" and the "provided plan" road routing strategies.

13.4. Problem-Solving Paradigm

Recent advances in computer technology have increased the ability of machines to emulate human cognitive functioning. Significant developments have occurred in machine or artificial intelligence (MI/AI), in particular expert systems and knowledge-based systems. These use symbolic methods, heuristic reasoning and neural networks rather than algorithmic, deterministic and stochastic computational procedures. These developments have provided machines with the capability to perform complex routine tasks autonomously, such as target recognition and sensor fusion, and more importantly, to assist the pilot flexibly and adaptively in the solution of problems external to the system i.e. mission problems, such as route planning and navigation. Machine intelligence can now be expected to offer support in making decisions, as well as off-loading unwanted tasks from aircrew in order to reduce operator workload. The prospect of utilising MI/AI has encouraged the use of the *problem-solving paradigm* for interface design. This focuses design effort on how the MPS interface can be created *to* help solve mission problems by supporting aircrew decision making. Most advanced MPS, whether or not employing MI/AI technology, should aim to function as *decision-support systems* for mission problem-solving. Thus, models for solving the problem of the interface design for decision-support systems are likely to the most relevant to advanced MPS systems.

13.5. Co-operative Functioning

It seems likely that a relatively high level of interaction is needed to support mission problem-solving with advanced MPS. Problem-solving involves decision-making and the use of cognitive skills, symbolic processes and the acquisition and manipulation of knowledge in the form of goals, strategies and plans as well as information, understanding and ideas. Several formulations have been proposed to describe the kinds of human-machine interactions or relationships that will be needed to support human problem-solving and decision making tasks based on concepts of *adaptive aiding* and *co-operative functioning.* In the concept of *distributed intelligence* (40), goal-directed co-operative work is achieved by the computer operating as an intelligent partner or co-worker, functioning as a full associate of the human. The *Electronic Crew member* or **EC,** introduced by Moss et al (41), conceives of the computer and avionics equipment as a mechanistic pilot associate operating across all systems. They argued that in a "blended" configuration, the human-machine system could allow the pilot to operate at a rule-based level, with the EC handling skill-based behaviour and formulating problems and proposing solutions to problems that would otherwise require knowledge-based behaviour.

MPS can be conceived as both pre-flight and in-flight forms of EC. In-flight planning and re-planning are likely to be more dynamic and time-pressured than pre-flight planning. Consequently, in-flight planning is likely to derive the greater benefits from the concepts of adaptive aiding and co-operative functioning. This should not limit thinking about the application of these concepts to the design of only in-flight systems. The benefits of advanced aiding concepts are likely to be substantial. They may soon transfer to ground-based mission-planning systems.

Much of the development of adaptive-aiding concepts for aircrew has occurred in the design of decision-support systems for airborne mission management. The USAF/DARPA Pilot's Associate programme, and subsequent work, has attempted to put into operation the concept of adaptive aiding through a functional component called the *Pilot Vehicle Interface* or PVI **(42, 43)**. The aim of the **PVI** is to manage the EC-pilot interface to conform to the pilot's intentions, providing assistance efficiently and unobtrusively while allowing the pilot to stay on top of the system control hierarchy, i.e. to stay in charge. This requires the incorporation into the control system automation of embedded models of human decision-making and performance, with monitoring of situational variables and pilot actions, and inferencing of pilot intentions in terms of embedded scripts, plans and goals **(44).** On the basis of this analysis, the PVI provides adaptive aiding at various levels of control: by either *transforming* the task, making it easier to perform; by *partitioning* the task with sub-goals divided between the pilot and the computer; or by *allocating* the task to automatic performance with pilot notification (45). These concepts of transforming, partitioning and allocating tasks provide a robust framework for thinking about the degree of automation of MPS functions.

The concept of *dynamic function allocution* (DFA) is a key characteristic of adaptive aiding that is responsive to the changing demands of dynamic situations. Essentially, in DFA the function and the associated tasks are assigned to the agent who has the time to attend to the task. Thus, the workload is shared in real-time during the planning task, or when airborne during the mission. Tasks are shared by the planner or pilot actively or explicitly authorising the computer to carry out the task, or by automatic task shedding with implied consent through the pilot pre-setting permissible workload levels, or through common knowledge of the mission objectives and overall governing rules of operation **(46.47).**

The provision of flexible automation categories, where the pilot or planner has the freedom to choose levels of automation or the *level of autonomy* (LOA) for each function, and to vary this choice as the tactical situation changes, probably is essential to avoid too rigid automation being imposed by the designer. The need for a discrete set of operational modes or autonomy modes, as a means of reducing confusion about responsibilities with dynamic function allocation and system autonomy, is discussed by Yadrick et al **(48).** Within each level, the MPS (or EC`s) authority would be well-defined and bounded, facilitating predictability, and rules would define the conditions and methods for changing levels. The pilot would be able to select any level, at any time. In flight, if the computer has difficulty performing at the selected level, it would inform the pilot and assume the highest level that it can. The current level of autonomy would be displayed at all times to the pilot.

Krobusek et al (49) propose LOAs that are set according to the pilot interaction or *operational relationship* (OR) desired for a particular EC sub-function. ORs range from where the pilot must perform the activity, to automatic performance by EC with or without pilot consent, or, when various conditions are met, with and without pilot notification. In other ORs, EC may remind or prompt the pilot to perform an action either autonomously or only with pilot authorisation. From this, pilot-selectable levels of EC autonomy are generated with specified ORs for each particular task and task cluster. Within an LOA, some clusters of functions will be more autonomous than others according to what is the most appropriate human-computer relationship and task allocation. Tailoring by the pilot of LOA functional clustering and dynamic task allocation are proposed to provide flexibility in responding to the changing temporal and loading demands of the dynamic mission environment.

13.6. Synthesis

The essential differences between co-operative functioning and the concepts of manual and supervisory control are summarised in Figure **8.** This illustration is used by Taylor and Selcon (50) to represent human-machine teaming arrangements. The diagrams in Figure **8** show schematic representations of the authority relationships between the human and machine components under the three systems concepts. Arrows drawn between the human **(H)** and machine (M) components indicate the direction in which authority is exercised. The location of the Pilot Vehicle Interface (PVI) is indicated as having changed from being concerned with the performance of tasks, to the delegation and monitoring of functions, and then finally to the communication and setting of goals. The changing allocation of responsibilities is shown for goals, functions and tasks. Under manual control, the human is responsible for both goals and functions. Under supervisory control, functions have been delegated to the machine. Under co-operative functioning, goals are assigned to the machine and some functions and tasks are shared under dynamic allocation, as shown by the composite symbols.

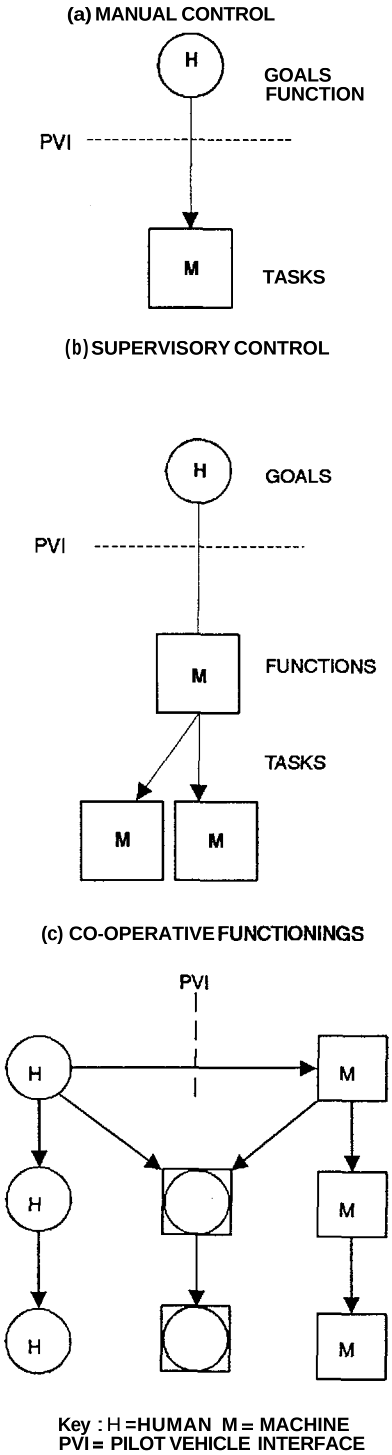

FIGURE 8- Systems Authority Concepts

14. EVALUATING THE CONCEPT OF CO-OPERATIVE TEAMWORK

14.1. Teamwork Model

The notion of man and machine working as an intelligent, co-operative partnership or team is considered to be central to the exploitation of MI/AI technology in human-systems design. The introduction of teaming concepts provides a broad social systems framework for thinking about human-machine co-operation. Consideration of the machine as a teaming resource raises a number of important issues. Foremost among these must be considerations of the generation and maintenance of team goals, the individual capabilities of team members, the functionality of team members, communication processes within the team, and where authority should be vested within the team.

A model of such teamwork has been proposed by Selcon & Taylor (51), derived from the social psychology of small group dynamics. This model is shown in Figure 9. Teams are considered to differ from small groups in the greater emphasis placed in teams on clear definition of goals, roles and structure. Teams have three distinctive characteristics:

(a) Co-ordination of activity, aimed at performing certain tasks and at achieving specific, agreed goals. Such co-ordination is dependent on trust between team members to be successful, since trust is the mechanism which allows co-ordination of effort to take place.

(b) Well-defined organisation and structure, with members occupying specific roles with associated power, authority and status, whilst exhibiting conformity and commitment to team norms and goals. Such organisation will define the allocation of functions and the locus of authority within the team.

(c) Communication and interaction between team members. These are referred to as team processes.

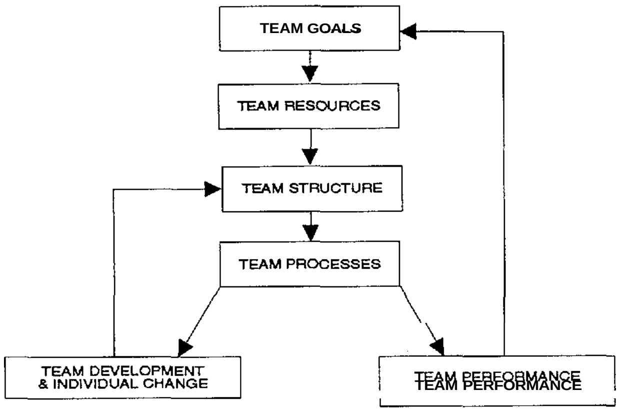

FIGURE 9- Teamwork Model

The system of relationships between the components of teamwork can be understood in terms of the team's goals, resources, and their effects on individual team members, team development and team performance. Such a model provides the framework for considering the implementation of adaptive aiding and decision-support in MPS so as to produce an effective team capable of best achieving the operational aims for which it was designed.

14.2 Model Validity

The validity of the teamwork model of co-operative functioning can be judged in terms of its sensitivity, diagnosticity and predictive power. Evidence for the validity of the model comes from two studies using a form of teamwork audit. The audit comprised a listing of twenty teamwork constructs, selected from the literature on teamwork and decision-support systems, and linked to the principal teamwork model components. In the first study (52), comparisons were made by experts of the evidence for the audit dimensions in technically immature (early) and mature (advanced) examples of aircrew systems for specific aircraft roles. These included systems for pre-flight mission planning and for in-flight mission management. In general, the mature system candidates scored higher and exhibited more of the teamwork characteristics than the immature systems. There was general support for the notion that there has been improvements in the embodiment of teatnwork goals, resources and structure requirements in aircrew systems for mission planning, but there was little evidence for progress in the development of teamwork processes for in-flight mission management i.e. the design of the cockpit interface. In other words, pilot - machine interface developments seem to be holding back progress in mission-system capability.

In the second teamwork model validation study (50), examples of good and bad teamwork taken from the RAF two-seat GR1 Tornado and single-seat GR5/7 Harrier aircraft operations were compared. Narrative descriptions were obtained of familiar problems on ground-attack tactical scenarios common to both aircraft operations in which interaction between the aircrew and the aircraft mission management systems contributed significantly to mission success or failure. Aircrew subjects (N=20) rated the contribution of the teamwork dimensions to examples of their experiences of good and poor teamwork in each scenario. The differences between the mean ratings for good and poor teamwork provided broad evidence for the relative sensitivity of the model dimensions. All four of the model dotnains, and 15 of the 20 teamwork dimensions, were sensitive to teamwork quality. The most sensitive dimensions were as follows:

(a) Goals
Achievement - High probability of success.
Common Structure- Shared understanding of meta/sub-goals.
Goal Clarity - Clearly defined performance objectives.

(b) Resources
Compatibility - Ability to combine/integrate/match.
Sufficiency - Enough expertise/ability/competence.

(c) Structure
Dynamic function allocation - Real time role/task distribution.

(d) Processes
Bidirectionality - Two way flow of information/feedback.
Common Knowledge Base - Shared understanding of situations.
Trust - Willingness to accept others' judgements.

This analysis provides some evidence for the relative importance of the system design requirements for co-operative teamwork. Achieving aircrew confidence and trust for levels of autonomous machine functioning in solving mission-critical problems is particularly important, and will require careful engineering of the human interface, including a two-way dialogue of explanation and information. The concept of levels of autonomy, or degrees of independent functioning, appear to be a weak contributor to teamwork. There will need to be a clear understanding of the rules governing function allocation, perhaps with smooth or "seamless" transitioning between levels of autonomy, thereby maintaining the flexibility needed in a rapidly changing environment. In order to cooperate adaptively, the computer will need to have knowledge of the mission goals and the agreed situation assessment, and to be able to anticipate the operators requirements.

15. CONCLUSIONS : CONSEQUENCES OF THE THEORY

15.1. Guiding Policy

The design of MPS should be driven by mission-goal objectives and evaluated by mission-goal measures of effectiveness, using logical, structured methods for human-centred design based on mission, function and task analyses. On the basis of analysis of the problem, and from mission analysis, determine the need for rigid and flexible response, and the requirement for planned and opportunistic behaviour, and then identify the requirement for automation and human system functioning. Where there is a need for human system functioning, as compared with a totally automated system, the objective should be to create systems with human control of system functioning and human involvement in the decision loop during both mission planning and mission prosecution. In human systems, automation should be governed by principles of co-operative functioning, and with the aim of supporting rather than replacing human decision making. This should be achieved by involving the planner in the decision loop, by providing feedback on performance with respect to mission-goal effectiveness through prediction and explanation, and by enabling the development and enhancement of human cognitive skills through the activation and refinement of appropriate knowledge and memory schemata.

15.2. Support Levels of Behaviour

The provision of human and MPS resources should be guided by consideration of sufficiency and compatibility. The aim should be to provide enough expertise, ability and competence, that is combined, integrated and matched in a compatible relationship to solve the problem of planning a successful mission. MPS should be conceived and designed to provide support for skill, rule and, if possible knowledge-based levels of behaviour. MPS should be used to automate routine functions requiring skill and rule-based behaviour, since this can most often result in reduced operator training and saving of operator task performance time. Where human cognitive skills are necessary to perform functions, MPS should seek to provide immediately the feedback on task performance that is necessary and sufficient to achieve the task objectives. Feedback on planning decision options should provide continuous, rolling predictions of the impact on sub-goals, goals and meta-goals, such as estimates of threat exposure, risk, and the probability of mission success. Feedback should be communicated through explanation and bidirectional dialogue at the MPS interface. Automation of functions should be avoided that require human involvement in monitoring of automation performance or human intervention in the event of system failure. MPS should seek to exploit advances in machine intelligence to act as aids in support of human decision-making and mission problem-solving.

15.3. Support Situation Assessment

A plan is only as good as the situation assessment on which it is based. Situations can change rapidly, particularly in the air. In flight, situation assessment, and the checking and revising of plans, can be relatively continuous activities that could be supported usefully by decision aids. Assistance could be provided in plan supervision to prevent overly rigid adherence to an invalid plan in a changing situation, by determining if the plan still enables the intended objectives to be met, and by repairing the plan to help meet the objectives. Advanced data fusion techniques have the potential to greatly assist situation assessment and decision making from diverse data sources, such as are available for MPS. Automated software programmes can assist in carrying out certain predictable routine functions, analyse and integrate data, make complex calculations and compute solutions to routine problems. But when dealing with new problems, where pre-established solutions are inappropriate, decision making **is** required at the, knowledge-based level. Decision aids for situation assessment and planning with new problems need to go beyond the surface representation of who or what is where etc., to help speculate on what it all means and to help make and evaluate predictions (53, 54).

There needs to be a common knowledge base and a shared understanding of the situation by the both MPS and the aircrew operator of the system. This requirement for a shared understanding can range from needing to draw inferences about hostile intent and risk, to predictions of the likely consequences of specific actions. In these more uncertain circumstances, aids are needed to amplify the judgement and intellect of the decision maker. Ideally MPS should seek to summarise the possible situations, using combining rules to present internally consistent representations. They should seek to depict the most important situations consistent with the evidence, and show the key abstract features or relationships not present at the surface level. They should seek to give indications of opportunities and risks in order to support the exploitation of opportunities. Finally, MPS should seek to give indications of the uncertainties that are most important to clarify and resolve.

15.4. Represent Uncertainty

Decision-support systems involve the manipulation of knowledge about uncertainties, and the aiding provided is inherently imperfect. The implementation of imperfect aiding systems requires feedback on performance if the operator is not to be drawn, through over-reliance on the system, into unacceptably high error rates *(55)*. **An** alternative is to ensure that a suitable degree of transparency exists in the system, thus allowing concurrent checking of system performance. Essentially, the planner needs to know where the uncertainty exists so that information can be treated accordingly. Failure to inform the planner of uncertainty will not only lead to errors but also to a loss in situational awareness. Awareness that uncertainty exists is crucial to an accurate understanding of the decision problem space. Poor communication of uncertainty is also likely to diminish trust in the system, as error rates increase, due to the perceived inaccuracy of the system. MPS should fuse the large amounts of incoming situational data into a cognitively compatible form, which the planner can use as the basis for the decision, thereby reducing the decision workload whilst maintaining knowledge of relevant uncertainty.

15.5. Support RPD

The consequences of RPD theory for system design are that MPS will need to cater in different ways for both novice and expert planners, for planning with decision making at rule-based and knowledge-based levels, and for planning under different degrees of time pressure. But, since improving speed of response is one of the prime objectives of advanced MPS, ideally planning systems should be flexible and capable of supporting both kinds of decision making strategies. Also, MPS should be designed to facilitate the learning transition from novice to expert planning and decision-making performance. It seems plausible that the kinds of non-RPD analytical and evaluative tools and aiding that are needed to train the novice to develop basic situation assessment and planning skills, routine procedures and condition-action rules, may be similar in principle to those required by the expert seeking assistance in handling a totally novel problem.

For applications requiring situation assessment and decision-making under time pressure, such as in-flight re-planning and plan repair, and contigency planning for unpredictable critical events, the RPD formalism suggests a need for MPS tools for rapid situation assessment. Some of the potential functions of an RPD tool for C3 decision-making, suggested by Noble (56), could include the following: actively creating multiple hypotheses; conjecturing about activities and uncertainties; building a model of expectations based on each hypothesis; seeking relevant information and testing confirmatory data; updating expectations regarding the plausibility of the hypothesis and the constraints and defaults; and evaluating competing hypotheses on the basis of strength as indicated by events consistent with the predictions. Integrated, real-time dynamic re-planning systems, using heuristic search and knowledge-based reasoning have been developed for the Pilots Associate programme, with aiding of situation assessment (57.58,). The aim is to provide integrated and cognitively compatible information, so that the pilot can immediately see the consequences of new routes generated by the planning aid to attack new targets or avoid new threats, and can intelligently make an informed decision to accept or reject the new plans.

15.6. Use Schema-Based Display Formats

Clearly, the *cognitive quality* and *cognitive compatibility* of the visual display of the situational data presented to the planner will be a major influence on situation assessment performed with MPS. MPS display formats should be designed and structured to be compatible with the situation schemata and scripts of the system operators. In one implementation of schema theory (59, 60), planning formats are based in the first instance on doctrinal knowledge templates, presented in a tabular and spread sheet form, showing the key abstract relationships that characterise the situations and activities, equivalent to rule-based, holistic, hierarchic scripts. From such doctrinal templates, facilities are provided to create individual instances representing a specific activity, hypothesis or plan, which predicts the types, times, locations and performers of events. This format needs to be efficient for evaluating data rather than abstract relationships. Accordingly, it is presented as map of the plan in order to facilitate evaluation. Formats will need to be designed to tolerate or to minimise the systematic errors associated with schema-based memory. For example, tracks with high hostile intent should be highlighted to minimise the problems of track fixation. Significant indications and warnings should be flagged and critical actions should be prompted to minimise inattention. Inappropriate actions should be identified and inhibited.

15.7. Encode Goals, Scripts and Frames

To achieve co-operative goal-directed activity, the computer must have embedded in its functioning some knowledge of system and sub-system goals, sufficient for it to provide appropriate support for mission problem-solving decisions. Thus, the capability of the machine can be seen to have been extended from performing tasks and accepting functions, to involvement in the maintenance and achievement of mission goals. Note that in this conceptualisation, the generation of goals remains a uniquely human function, maintaining the human in charge at the highest level of system control. It is important that the goals should comprise clearly defined performance objectives, that there should be a shared understanding of the structure of the goals, including meta and sub-goals, and that the goals should be realistic and achievable, with a high probability of success.

15.8. Generate Trust in Automation Functioning

Difficulties in gaining aircrew acceptance and trust for MPS involvement in mission-critical decision making, necessitate that the machine support be configured to aid the planner in making decisions, rather than acting as a substitute for human decision-making. Trust should be based on evidence of proven performance. Achievement of the required level of trust and confidence may require the MPS to be more proficient at the task than the planner (61).

15.9. Provide Adaptive Aiding

Aiming to provide MPS which reduce aircrew workload and improve situational assessment and decision making is not necessarily sufficient. The key objective should be to use machine intelligence to improve the matching or integration of machine and human resources for optimum mission performance. A high level of integration of human and machine resources can be achieved by providing adaptive aiding and dynamic function allocation that is responsive to changing demands of dynamic situations. In flight mission planning is likely to benefit most from dynamic function allocation. But the concept is applicable to pre-flight planning where a standard or *universal* MPS is employed to support a variety of aircraft roles each with different and varying demands. Dynamic function or task allocation has the potential to use human-computer system resources more effectively in a dynamic environment than can be achieved by any static, fixed allocation.

REFERENCES

1. Broadbent, D.E., "Planning and opportunism". The Psychologist: Bulletin of the British Psychological Society. Vol 6, pp 54-60, 1993.
2. Hale, A.R. and Gordon, A.I. "Individual behaviour in the control of danger". Amsterdam: Elsevier, 1988.
3. Meister, D., "Psychology of System Design", Elselvier: Amsterdam, 1991.
4. Doring, B., "Systems ergonomics: An approach for developing well-balanced, cost-effective man-machine systems." *In* "The Human as a Limiting Element in Military Systems". Vol. 1, NATO DRG DS/A/DR (83) 170, Brussels: NATO Defence Research Group, 1983.
5. Beevis D. (Ed),"Analysis Techniques For Man-Machine Systems Design". NATO DRG Technical Report AC/243 (Panel **8)** TR/7, Volume 1, Brussels, Nato, 1992.
6. NATO MAS, "The Application of Human Engineering to Advanced Aircrew System Design, STANAG 3994 AI, Military Agency for Standardisation, NATO HQ, Brussells. 1991.
7. McMillan, G.R., Beevis, D., Salas, **E.,** Strub, M.H., Sutton, R., and Van Breda. Eds. Applications of Human Performance Modelling to Systems Design. New York: Plenum, 1989.
8. Boff, K.R. "Integrated Ergonomics into System Design". CSERIAC Gateway, Vol. 1, No. 2, pp 1-3,1990.
9. Boff, K.R. and Lincoln, J.E. Engineering Data Compendium: Human Perception and Performance. AAMRL Wright-Patterson AFB,Ohio, 1988.
10. AGARD , "Mission Planning Systems for Tactical Aircraft", Advisory Report 296, NATO AGARD, Neuilly Sur Seine, 1991
11. Rogers, S.P. & Spiker, V.A. "Fundamental Design Requirements for a Mission Planning System for High Performance Aircraft", Technical Report 641-3, Anacapa Sciences, Santa Barbara, CA., 1986.
12. Rogers, S.P. & Spiker, V.A. "Functional Capabilities of Mission Planning Systems", Technical Report 625-12, Anacapa Sciences, Santa Barbara, CA., 1988.
13. Tolman, E. C. "Purposive behaviour in Animals and Man", Appleton-Century-Crofts,1932.
14. Tolman E.C. "Cognitive maps in rats and men". Psychological Review, 55, pp 189-208, 1948.
15. Hebb, D.O. "The Organisation of Behaviour". New York: Wiley,1949.
15. Lashley, K.S. The Problem Of Serial Order In Behaviour. In, L.A. Jeffries (Ed), Cerebral Mechanisms in Behaviour: The Hixton Symposium. New York: Wiley, 1951.
16. Miller, G.E., Gallanter, E. & Pribram, K.H. "Plans and the Structure of Behaviour" New York: Holt. 1960.
17. Craik, K.J.W., "Theory of the human operator in control systems", British Journal of Psychology, Vol. 38, pp 56-61 & 142-148, 1947.
18. Moray, N."Feedback and the control of skilled behaviour". *In*, D. Holding (Ed), "Human Skills", Chichester: Wiley, 1981.
19. Powers, W.T., "Behaviour- The Control of Perception", Chicago: Aldine, 1973.
20. Neisser, **U.,** "Cognition And Reality: Principles and Implications for Cognitive Psychology", San Francisco: Freeman, 1976.
21. Anderson, J.R., "Acquisition of Cognitive Skill", Psychological Review, Vol. 89, No. 1, pp 369-406, 1982.
22. Thorndike, P.W. & Hayes-Roth, **B.** "Differences in spatial knowledge acquired from maps and navigation". Cognitive Psychology, *14*, pp 560-589,1982
23. Bartlett, F.C., "Remembering: A study in experimental and social psychology", London: Allen &Unwin, 1932.
24. Schanck R.C. & Abelson R. "Scripts, plans, goals and understanding. Hillsdale NJ: Erlbaum, 1977.
25. Endsley, M., "Situational awareness in dynamic human decision making: Theory", *In* Proceedings of the CAHA Intemational acaonference on Situational Awareness in Complex Systems", CAHFA, Orlando, 1993 (In press).
26. Rasmussen, J.E., "Skills, Rules and Knowledge: Signals, signs and symbols, and other distinctions in human performance models". IEEE Transactions on Systems, Man and Cybernetics, *13*, pp 257-266, 1983.
27. Rasmussen, J.E., "Information Processing and Human-Machine Interaction: ***An*** Approach to Cognitive Engineering". New York: North Holland, 1986.
28. Klein, G.A:, Orsanu, J., & Calderwood, R. "Decision Making in Action:Models and Methods", Norwood N.J: Ablex, 1993 (In press).
29. Shepard, R.N. & Metzler, **J.** "Mental Rotation Of Three-Dimensional Objects", Science, *171*, pp 701-703, 1971
30. Shepard, R.N. & Cooper, L.A., (Eds). "Mental Images and their Transformation". Cambridge, MA: MIT Press, 1982.
31. Aretz, A., "Spatial Cognition and Navigation", *in* "Proceedings of the **33rd** Annual Meeting of the Human Factors Society", Santa Monica, CA: Human Factors Society, pp 130-134, 1989.
32. Richardson, A., "Mental Practice: A Review and Discussion" Research Quarterly, ***38,*** pp 95-107 & 262-273, 1967.
33. Minas, S.C., "Mental Practice of Complex Perceptual-motor Skill. Journal of Human Movement Studies, ***4,*** pp 102-107, 1978.
34. Sholl, M.J., "cognitive Maps as Orienting Schemata". Joumal of Experimental Psychology: Learning, Memory, and Cognition, *13*, pp 615-628, 1987.

35. Card, **S.K.,** Moran, T.P. & Newell, A., "The Psychology of Human-Computer Interaction. Hillsdale, N.J: Erlbaum, 1983.

36. Norman, D.A., "Cognitive Engineering". *In* Norman, D. A. & Draper, S.W.,(Eds), "User-Centred Systems Design: New Perspectives on Human-Computer Interaction", Chapter 3, pp 32-61. Hillsdale, N.J: Erlbaum, 1986.

37. Taylor, M.M.,"Layered protocols for computer-human dialogue. I: Principles." International Journal of Man-Machine Studies, Vol 28, pp 175-218 1988.

38. Egglestone, R. E., "Machine Intelligence and Crew-Vehicle Interfaces". In: E. Herr and H. Lumm, Eds. "Machine Intelligence and Autonomy for Aerospace Systems". AIAA, 1988.

39. Sheridan, T.B., "Supervisory control of tele-operators". *In,* Bernotat, R.K. and Gartner, K.P., (Eds), "Displays and Context", Swets and Zeitlinger, 1972.

40. Goodson J., Zachary, W., Weiland, W., & Hopson J. "Distributed intelligence systems: AI approaches to co-operative man-machine problem solving in C3I". AIAA Computers in Aerospace. Conference. Hartford CT, USA, AIAA-83-2316, 1983

41. Moss, R., Riesing J., and Hudson N. "Automation in the cockpit: Who's in charge?" Proceedings of the 3rd SAE Aerospace Engineering Technology Conference, Long Beach, CA.1984

42. Andes, R.C. "Adaptive aiding in complex systems: an example", *in* "Proceedings of the IEEE 1987 Conference on Systems, Man and Cybernetics", 1987.

43. Lizza C.S., Rouse D.M., Small R.L., and Zenyuh J.P. "Pilot's Associate: An Evolving Philosophy" *in* "The Human-Electronic Crew: Is the Team Maturing?" RAF Institute of Aviation Medicine, PD-DR-P5, April 1991. Wright Laboratory, WPAFB, WL-TR-92-3078, July 1992.

44. McCoy, M. and Boys, R. "Human performance models applied *to* intelligent decision support systems" *In* "Proceedings of the IEEE National Aerospace Conference",1987.

45. Rouse, W. B., Geddes, N. D. and Curry, R. E. "An architecture for intelligent interfaces: Outline of an approach to supporting operators of complex systems". Human-Computer Interaction. Vol 3, (2), 1987

46. Emerson T J, Reising J M , and Britten-Austin H G . "Workload and Situational Awareness in Future Aircraft", *in* "Recent Advances in Cockpit Aids for Military Operations", Royal Aeronautical Society Proceedings, London, 1987

47. Boys, R. and Palko, K., "Automation and dynamic allocation: Engineering issues and approaches". *In* NAECON Proceedings, IEEE New York, 1988

48. Yadrick, R.M., Judge, C.L., and Riley, V.A. "Decision Support and Adaptive Aiding for a Battlefield Interdiction Mission". *In* "The Human-Electronic Crew: Is The Team Maturing?", PD-DR-P5, RAF Institute of Aviation Medicine, Farnborough, April 1991.

49. Krobusek R. D., Boys **R.** M., and Palko, K. D. "Levels of autonomy in a tactical electronic crew member". *In* "The Human-Electronic Crew: Can They Work Together?", BSD-DR-G4, RAF Institute of Aviation Medicine, Farnborough, December 1988. (WRDC-TR-89-7008, 1989).

50. Taylor, R.M. and Selcon, S.J., "Operator and automation capability analysis: Picking the right team". *In,* AGARD-CP-520, Paper 20, NATO AGARD: Neuilly Sur Seine, April, 1993.

51. Selcon, S.J. and Taylor, R.M., "Psychological Principles for Human-Electronic Crew Teamwork", *in* "The Human-Electronic Crew: Is the Team Maturing?" . RAF Institute of Aviation Medicine, PD-DR-P5, April 1991.Wright Laboratory, WPAFB, WL-TR-92-3078, July 1992.

52. Taylor, R. M. and Selcon, S. J. "A Teamwork Model of Pilot Aiding: Psychological Principles for Mission Management System Design". AGARD-CP-504. Paper 9, NATO AGARD: Neuilly Sur Seine, March 1992.

53. Noble, D. "Theory to guide the design of situation assessment aids for decision-making". *In* Proceedings of the 8th MIT/ONR Workshop on C3 Systems. Office Of Naval Research, Washington D.C., 1990.

54. Brander, G.N. & Scard, N.J., "Cognitive Models of Decision Making", DRA Tech Memo, Portsdown, Portsmouth, 1993 (In press).

55. Selcon S.J. and Taylor, R.M. "A Review of Decision Support Systems (DSS) and their Applications". IAM Report No. 714, May, RAF Institute of Aviation Medicine, Farnborough, 1992.

56. Noble, D., "Situation Assessment and Planning Technology: Cognitive Foundation, Data Fusion, Implementation and Decision Support Architecture". Report to DRA Maritime C3 Division, Portsdown, Hants, 1993.

57. Bate, **S.** and Stanley, K. "Heuristic Route Planning: An Application to Fighter Aircraft. NAECON Proceedings, IEEE: New York, 1988.

58. Corrigan, J.D. and Keller, K.J. "Pilots Associate: An Inflight Mission Planning Application", AIAA Guidance, Navigation and Control Conference Proceedings, August, 1989.

59. Noble, D. & Mullen, R. "Information presentation for distributed decision making". *In* Johnson, F. & Lewis, A., (Eds), "Science Of Command And Control: Coping with Uncertainty". **pp** 127-133. AFCEA Interactive Press: Washington D.C. 1988.

60. Noble, D., "Schema-based knowledge elicitation for planning and situation assessment aids". IEEE Transactions on Systems, Man and Cybernetics, Vol. 19, pp 473-482, 1989.

61. Rouse, W. B. and Morris, N. M. "Conceptual design of a human error tolerant interface for complex engineering systems", Automatica, 23, pp 231-235, 1987

HUMAN FACTORS OF MISSION PLANNING SYSTEMS: APPLICATIONS AND IMPLEMENTATION

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SUMMARY

It was apparent from the beginning of the work carried out by the Joint Working Group in Phase One, that the successful application and implementation of human factors considerations were an essential part of the design of Mission Planning Systems (MPS). Although these considerations were discussed in Phase One, in Phase two human factors were investigated in greater detail.

It was considered essential that, as with all systems design, a full understanding of the information requirements and information flow of MPS in Pre-flight, In-flight and Post-flight situations was understood, as well as the dependencies under which the system must operate. Ideally, each component should be complimentary and be designed in accordance with requirements of each component as well as the 'mission' system as a whole.

The Phase One report included descriptions of the emerging MPS including the ergonomics and the interface of each system. There was a high degree of similarity apparent in both approach and implementation.

The Phase Two report explored many of the issues raised in greater detail, particularly that of trust that aircrew must have in the systems and the subsequently planned mission and the interface through which the user must communicate with the system.

1. Importance of Human Factors in Mission Planning Systems

The capabilities of mission planning systems are developing and expanding rapidly due to both 'push' from perceived user and service requirements but more significantly, 'pull' from the developing technology. This increased capability and complexity has heightened the importance human factors in MPS design and development.

Mission rehearsal and training is increasingly becoming a capability of developing MPS and the associated human factors issues need to be addressed. A further capability, now becoming possible is the planning or re-planning of missions in flight. The implementation and operation of such facilities needs to be managed together with other cockpit activities and not implicitly or explicitly, increase workload, particularly during critical mission phases. The introduction of Artificial Intelligence/Intelligent Knowledge Based system techniques in MPS as well as in mission avionic systems will impact on the human factors of the system, particularly how the pilot interacts with such an 'intelligent' system.

From Phase 1 of the report it was apparent that in existing mission planning systems:

- integration of mission information was largely performed by either the crew flying the mission or occasionally a specialist mission planner.

- the manual aspects of planning carried out by the crew provides a detailed appreciation of the many mission elements, providing an element of mission rehearsal. In developing more automated systems these may be lost.

- a large amount of time is spent on mundane data entry tasks.

From the emerging and planned future systems it was apparent that:

- there was increased use of more centralised databases providing centralised support;

- there would be a capability for some form of mission rehearsal;

- there was a reduction in the manual data entry tasks;

- there may be a limited form of in-flight mission planning.

One reason for the importance of human factors in MPS is the increasing reliance on MPS to successfully carry out the mission, and the increasing sophistication and automation as well as the design of higher level tasks into the avionics systems/mission planning systems.

2. Implementation of Human Factors

The increasing implementation of human factors into the design of many MPS is now taking place due to the growing use of standards. In the past the application of the developing technology, especially the advances in computing power, has been the design driver, often with little regard paid to the users requirements, This design approach has resulted in MPS, as with other systems, not taking full advantage of the technological advances.

The introduction of standards (such as STANAG 3394AI and MIL-STD-1472D, iMIL-H-46885, as well as initiatives such as MANPRINT) force the design to take account of the user's requirements. This causes the design to be based on the man-task relationship and not on a task-system basis alone. The design of the interface should be considered the 'task driver' and should be designed taking into account the cognitive aspects of the task interaction with the system as a whole.

This developing capability has also increased the importance attention paid in the design to the optimum allocation of function between operators and the system. A complication is that hardware and software components are developing capabilities that were previously only possessed by the human component. This can and often does lead to excessive demands for automation.

With this blurring of the boundaries between what is optimally performed by the system and what by the man, even greater emphasis has been placed on allocation of function. Inappropriate allocation may result in underload/ overload for any system component or undue reliance and trust placed in the system by the operator.

The concept of dynamic task allocation, where the level of system autonomy is dependent on the task and the operator's needs, when applied to MPS, may improve overall task performance when compared to static task allocation.

Work such as the development of the concept of Operational Relationships attempts to define the relationship between the operator and an automated system. This study defined ten categories of Operational Relationship ranging from OR 'A' where the activity is performed manually by the pilot to OR 'G3' where the system performs the task autonomously. Future MPS will benefit from the work carried out in this field in the development of 'Electronic Crewmember' systems for future single-seat combat aircraft. Research programmes such as 'Pilot's Associate' in the US, 'Co-Pilote Electronique' in France and the UK 'Mission Management Aid' contain major elements of the mission planning task, Each programme regarded the appropriate implementation and application of human factors as critical.

The mission planning task is performed by the aircrew or in some cases by specialist mission planners. In the development of an MPS that automates much of the actual planning process, particularly with the introduction of IKBS systems, the human 'hands on ' element may be lost. This may have several implications in terms of the elements of mission rehearsal that are implicit when the mission is planned and in the level of trust and confidence the crew may have in the planned mission.

3. Trust and Confidence

Trust and confidence in the mission plan is essential if aircrew are to rely on the mission plan for assistance on decisions that may be mission critical, particularly if such decisions and tasks are carried out by the system with implied consent. A lack of trust or confidence will not allow the full potential of the man-machine partnership to be attained.

The degree of trust that aircrew may have in an automated system is dependent on many factors which change over time both pre-mission and during the mission. Initially trust appears to be based on the predictability of the system. As the user becomes more experienced with the system, trust becomes based on dependability when in difficult situations the system is seen to consistently provide useful information.

The level of acceptance and trust aircrew may have in an automatically planned mission dictates the level of autonomy they allow the system and the operational relationship under which they wish to operate. An understanding of the requirements necessary to instil trust and confidence in a system is vital if such elements are to be designed into the system. This applies to ground based, airborne and particularly to embedded MPS as part of an integrated avionics suite.

Elements thay may promote trust and confidence include:

3.1 Interface

The MPS interface, and consequential interaction, between the pilot and the system may be designed to encourage the development of trust and confidence as the mission is planned. Such an interface should have such characteristics as:

- Displaying confidence levels. If the system is able to assign a confidence level to a decision made, the pilot is then able to make a value judgement based on this and other information.

- Displaying the decision process when requested. The derivation of a decision should be displayed so as to be easily and quickly understood by the pilot, (including sub-decisions, weightings etc).

- Allowing the pilot to question a decision/plan. The pilot should be able to question or alter specific sub-decisions to view the effect on the final decisions.

- Clarity of level of autonomy/operational relationships. The interface should unambiguously display to the pilot whether the locas of control is with the pilot or the system.

- Allow pilot override of system decisions. A perennial pilot requirement of any automated system is that they have the capacity to override any of the systems decisions.

3.2 Logic/Reasoning

The logic and reasoning employed or perceived as employed by the MPS can be a major factor in the level of trust in and acceptance of a system planned mission.

- The 'model' to which the system operates should match as closely as possible the pilots own cognitive model of the planning process, This would allow the pilot to 'map' the decision process on to his own thereby increasing his understanding and therefore acceptance of the decisions made.

- The system should be tailored to match an individual pilot's abilities and preferences. If individual differences are significant, the decision making process should be tailored to individual pilots for the match to be effective.

3.3 Who Plans the Mission?

The level of trust and confidence the pilot has in a planned mission may be dependent on the involvement the pilot has in the planning process, either before or during the actual mission.

- What, if anything, does the pilot gain in terms of a 'model' that may increase confidence, when he plans the mission? He may gain an element of mission rehearsal.

- If this 'model' is lost does the pilot therefore,have less confidence in missions planned by specialist mission planners, eg. US Navy TEAMS. If so, is he less able to react effectively to unplanned events.

- If the mission is planned by others, the interface should be designed to allow the mission to be rehearsed in some form and to enable the pilot to examine 'what if' situations. This feature requires careful consideration due to the knowledge that may be gained subconsciously during the manual planning process. If the process is automated, such knowledge must be transferred by the system to the aircrew.

- There should be the capacity for the pilot to delegate planning tasks in terms of both quantity and quality. This must be reflected in the operational relationship between the pilot/crew and the MPS. This may be dynamic.

- Level of autonomy and allocation of function. For the pilot/crew to develop trust in the system the optimum allocation of function between the pilot and the MPS must exist and be unambiguous. A small set of levels may exist, specifying the degree of autonomy. The pilot may be able to set the level as a consequence of the mission plans.

3.4 Development of Trust and Confidence

How would a pilot gain confidence during the introduction of an MPS? He may gain confidence:

- If the system is seen to produce 'better' plans than the pilot using the previous mission planning methodology. 'Better' may be difficult to define.

- If the system consistently produces 'better' plans. If the system is seen to be consistent and dependable then the pilot may develop faith in the systems abilities.

- If the pilot develops faith in the system's abilities and reliability over time.

3.5 Introduction of the System to Develop Confidence

How would the introduction of an MPS into service or to the pilot affect trust and confidence?

- Initial introduction of the automated system as a support or decision aid, increasing in complexity and significance of the support and advice offered. Gradually, the pilot would develop trust as the system complexity increases.

- The system is seen to learn and develop using the individual pilots knowledge. The pilot develops confidence in the systems abilities, which would be seen by the pilot as an extension of his own ability.

- The system evolves with the pilots capabilities from commencement of flying training.

- The system is predictable.

3.6 Training

Training would play the major part in developing trust in a highly automated MPS, as training will develop trust and familiarity which are critical factors if the pilot is to accept the system.

3.7 Other Factors

- Pilots are becoming more computer literate due to exposure to computers at school etc, and thus may be willing to accept and trust automated systems that pilots of previous generations would have rejected.

- The capabilities, reliability etc. of the system is passed on to the pilot by word of mouth from other experienced aircrew ie. the system develops a 'folklore',

4. The Human Computer Interface

The interface of a MPS is the medium through which a user communicates with with computer system and vice versa. The form of interface has a major influence on how a user views and understands the functionality of the system. The user interface is that aspect of the system with which the user comes into contact with both physically and cognitively.

The user interface has a specific form of dialogue used to facilitate user-computer interaction. The dialogue enables the user to 'map' the task to the functionality of the system.

An appropriate and well designed interface allows the user to decompose the overall task into sub-tasks and map these to the systems functions. An inappropriate or poorly designed interface may require the user to breakdown the task in an illogical manner and the ensuing mapping is prone to errors.

The essential element of interface design therefore involves the comprehension of the user tasks and the user's 'map' of sub-tasks. This in turn requires an understanding of the users themselves and the influence on their behaviour of the context in which they work.

Identification and understanding of the intended users is vital if the interface as well as the overall system, is to be effective. During the development of a MPS for the Tomahawk missile system, it was assumed that the operator would have extensive low-level flight experience eg. aircrew. In reality, the missions began to be planned by intelligence personnel who had little or no flight experience. This put additional demands on the MMI, as non-pilots fail to appreciate the importance of energy management.

A factor crucial in the design of the man-machine interface is to ensure that the interface is compatible with the mission planning processes, which may be dependent on factors such a national mission models, subjective models etc. The interface must also be flexible in responding to changes in requirements made upon it as the demands of the mission change. To meet these requirements human factors must be incorporated in the design process at an early stage.

Extensive research effort is carried out in the development of Human-Computer Interaction (HCI) for commercial computer systems. Such developments have an obvious direct application to ground based MPS. This research effort coupled with enormous increase in the processing abilities and reduction in costs of commercial systems has started a trend by the military towards the use of commercial computer technology and systems for specific military applications. This is particularly true for MPS and associated HCI.

Commercial software standards are becoming increasingly embraced, as seen by the proposal to adopt the UNIX operating system and the X-Windows user interface as the standard environment for the next generation of workstation-based systems. The next generation MPS for the US Air Force, the Air Force Mission Support System (AFMSS) will run on UNIX on commercial workstations and will use X-Windows as the interface.

X-Windows is a specific and most widely accepted forn of Graphical User Interface (GUI). User interaction with GUI may be performed by the manipulation of on-screen graphics eg. windows, icons and menus by a mouse or rollerball. The interface has been found to be easily used by both novices and experts. All user's actions are represented on the interface and any change is immediately visible. By representing the system in this form, the GUI can reduce the cognitive load of the user, as well as reducing the overall memory task by the need to remember fewer, simpler commands. Cognitive load may be increased by poor design or implementation.

These characteristics convey a high degree of 'transparency' to a GUI. This allows the user to deal only with the task and not allocate unnecessary resource to the operation of the system. Thus such interfaces are able to reduce the cognitive effort required to perform the task eg. plan a mission.

GUI have the following characteristics:

- The object of interest is always on the screen.

- Any changes made by the user are immediately displayed.

- Physical actions are used to interact with objects.

- It is possible to reverse actions taken

Such characteristics provide benefits such as:

- Novices may learn the basic functionality of the system quickly.

- Experts are able to work rapidly and may be able to define new functions and features.

- Knowledgeable but intermittent users may retain operational concepts.

- Users may be able to see if their actions are furthering their goals, and if not, they may be able to change the direction of their activity.

Another characteristic of GUI is that given the immediacy of feedback, the likelihood of making substantial errors is reduced and if made, errors can be quickly corrected.

However, there are disadvantages that may need to be considered. GUI cannot be configured as highly automated systems, or if automation is embedded within the system, few of the desirable characteristics will remain intact. In any highly automated system the 'distance' between the users intentions and goals and the systems increases, as the interface may have no direct influence on the system.

The sense of 'engagement' may also be reduced as a consequence of the users unfamiliarity with the systems logic.

This means that if the MPS is to be highly automated due to the need to reduce the time needed to plan a mission etc, GUI may not be the most appropriate form of interface to employ. However, the beneficial attributes associated with GUI should be considered.

4.1 Adaptive Interfaces

One of the most powerful methods of supporting the information processing at an inferencing level is by modelling the reasoning and the human-decision making process. This is the objective of the Adaptive (or Intelligent) Interface. The Adaptive interface operates on a co-operative basis, where functions are shared between man and machine. These interfaces reflect the flow of information and locus of control between man and the system. Adaptive also refers to the support the system offers, adapting to the needs and capabilities of the user, by taking into account his limitations. Adaptive interfaces may therefore be particularly suitable for inflight mission planning, where data fusion may be taking place.

Adaptive interfaces are aimed at assisting operator performance only when support is needed. This approach is an alternative to the concept of automating the entire task if the suitable technology is available. This approach envisages automation as a "back up". A default level would be where all tasks are manual; automation will only occur when specifically requested by the operator or when the performance level is considered unacceptable. This approach to the design of automated support should result in models of interaction which take into account both the variation in task demands and the mental resources the aircrew have available.

The major interface design topic addressed by the adaptive interface is the issue of the transfer of control between the operator and the system, and the allocation of tasks. The interface plays an important role in organising the distribution of activities. With such systems the interface operates as an executive assistant, whose key function is that of recognising human limitations and organising task agendas. Sub-systems monitor operator performed tasks and derive an assessment of the pyscho-physical performance, evaluate the complexity of the following task and produce a strategy on how to assist the operator. It can operate as an on-line expert system which through co-operation with other avionic systems may:

- Receive information and requests from sensors, subsystems and operator,

- Assign priorities.

- Evaluate time criticality.

- Schedule requests, messages and information into task sequences.

In order to reduce arbitrary decisions, the interface manager is envisioned as a hierarchical representation of goals, plans and actions. Therefore task allocation is based not only on a consideration of the current demands, but on the evaluation of impending problems.

Fully fledged adaptive interfaces as yet may not exist but their importance in all aspects of cockpit automation ensure their inclusion in many research programmes eg. the Pilot Vehicle Interface in the Pilots Associate Programme. A major difficulty encountered with such an approach is the reluctance of aircrew to accept such automated support. Reasons for this reluctance are many, but on the understanding that this may be an area where the limitations of the system become most apparent, it may be concluded that this is an area where research is required. Effort should be devoted to the understanding of the co-ordination and communication processes between man and systems in multi-tasking environments.

The acceptance by operators of decision support is based on the capability to establish trust and confidence. A major problem is the paradox of allocating control and authority to the system, while final responsibility remains with the human operator. Thus research effort is being devoted to understanding the means by which trust and confidence may be developed and maintained.

5. Interfaces for Artifical Intelligence/ Intelligent Knowledge Based Systems (AI/IKBS)

The adaptive Interface may be the most suitable to systems incorporating large AI/IKBS elements.

If the MPS includes a substantial AI/IKBS element the interface must support these functions. Although the interface may be based on existing interface types, there may be a requirement to support the display and interaction of other forms of data.

An example is the possible requirement to display on request, and in a form that is readily comprehensible to the aircrew, the domain knowledge that the system is based upon. The interface should enable the aircrew to question a decision, request a justification and examine the logic.

With future systems it should be possible to maintain a model of the operator's current knowledge state and therefore tailor the response specifically to the operators current needs. This is in accordance with the concept of the 'electronic crewmember'.

6. Prototyping

An effective and appropriate MPS interface is the product of the interface being a major component of an iterative design process. Iterative design has been facilitated by the ability to create and use software prototypes which simulate the functionality and operation of a system. A prototype should be inexpensive and take only a short time to develop, hence the use of the term rapid prototyping. A prototype interface is an interface that:

- actually works.

- may be discarded or evolve into the final system.

- be built quickly and cheaply

- forms part of an iterative design process and which therefore can be modified and re-evaluated.

Prototyping is an essential and integral part of the iterative design process and allows constant evaluation by the operators as part of programmed operator trials, which allows users to develop an understanding of and confidence in, the new system. It allows early application of human factors to the design and the early evaluation by potential operational users. A dynamic prototype interface with which actual or potential operators can interact will encourage task expertise to surface, which can be fed back into the interface design. Prototypes can be used by the interface designer to elicit information from the operators on the most appropriate system structure and functionality, operation, required representations and operator support needs.

7. Mission Rehearsal

The concept of mission rehearsal is becoming an increasingly important future Capability in mission planning systems, due to the availability of graphics engines. The requirement to support this function and the impact on the interface requires greater investigation.

Rehearsal may take place as part of the planning process or as a separate function after the mission has been planned. Technology plays an important role in producing the requirement for mission rehearsal. Automation is reducing the active "hands on" participation of the planner and the cognitive model the planner would build up unconsciously during planning is lost

Increasing technology may assist the rehearsal of the mission by providing the systems capabilities to support rehearsal. This may compensate for the decrease in familiarisation with the mission.

To ensure the design of the interface is able to support mission rehearsal the requirements for mission rehearsal and the implications for the planning process as a whole must be understood.

Rehearsal capabilities are already present, to some extent in emerging systems or systems under development. However they are part of the planning process and the rehearsal aspects are implicit. Development is directed towards more explicit support to the rehearsal process.

Emerging mission planning systems allow a level of rehearsal to take place. For example, they may provide three-dimensional perspective views, others provide "out of the cockpit'' views with the ability to zoom in and out of the view and FLIR/radar images. A further rehearsal function is the capability to "fly through" the route in real time or slowly through particularly difficult or hazardous phases of the mission. The role of the mission planner will undoubtedly change with the introduction of emerging planning systems, due to the introduction of capabilities such as mission rehearsal.

8. Features of Mission Rehearsal Interface

MPS should be capable of supporting mission rehearsal both during the planning process and after the plan has been finalised. Time availability and the type of man-system collaboration, are the two main factors that affect rehearsal potential.

When time is available, planners pay conscious attention to critical aspects of the mission, and evaluate possible alternatives. If the planner is able to choose from a number of alternatives, then he makes an implicit correlation between local detailed solutions and the global overall plan. This harmonisation process is dependent on the level of interaction that a given planning system makes possible. Thus rehearsal, can be considered a technique to assess a plan's suitability by taking into account significant factors such as tactics, threats, deconfliction etc and for the planner to develop confidence in the plan.

The time available and type of man-system collaboration are considered differently when the operational needs for rehearsal after the mission has been planned are considered. A simple model which describes the inter dependency between these two factors can be defined.

The model is based on three dimensions, high, moderate and low time constraints and the modality of the system planner co-operation.

When time pressure is low, the modality of the interaction between the system planning may be high. The automated support can thus be modelled accordingly eg. by allowing the planner to assign tasks on-line and by allowing him full control. Rehearsal is therefore implicit in the process, since the operator is self paced.

Where the time pressure is moderate, automated support can be configured to offer pre-solutions based on constraints imposed by the planner. As a consequence, rehearsal capabilities may concern specific critical mission phases of the mission.

Where time pressure is low or moderate, the planner is directly involved in the planning process and the system provides rehearsal facilities where required. After the mission has been planned, rehearsal may take place on the ground before take-off or during the flight.

Mission review, where a mission is "re-flown" to review aspects of the mission may be another function of the rehearsal process.

Another important characteristic is the level and quality of "realism" that is considered necessary. Where realism is critical full simulation facilities may be necessary eg. US Special Operations Forces MPS. The cost of such rehearsal/ mission planning systems will ensure that only those missions, and more probably only parts of missions, where such a level of fidelity is required actually employs such systems.

9. Advanced MMI

As the computing power available increases substantially, the management of this power by the user is largely constrained by the interface between the user and the system. Such MPS will range from small field-based units to shipboard mission rehearsal systems and the users may range from specialist mission planners to aircrew.

Multi-sensor interfaces will enable the generation of a 'virtual' environment, producing an 'immersion' interface that will enable planning and rehearsal of a mission to a high degree of fidelity.

How much virtual reality is considered enough for 'immersion' reality and how much for 'visually augmented' reality is the subject current research, is ultimately dependent on, at least in the short term, the technology available.

10. Conclusion

Several key issues became apparent as the working group examined the application and implementation of human factors in Mission Planning Systems, including design, development and operation. The numerous influences on the operational use of MPS, both current and future, require the systems to possess certain characteristics to ensure the usability and acceptance of the system. These key issues include:

- the requirement for the interface to be intuitive and not interpretative due to factors such as workload, time constraints and trust,

- the system should degrade gracefully whilst informing the user of its current capabilities and limitations.

- the system should be fully verified and validated to ensure user acceptance. This is possible early on in the design process by the use of rapid prototyping techniques.

The Mission Planning System, whether in-flight or pre-flight and whether on-board or ground based presents both an opportunity and challenge for the successful application and implementation of human factors.

Computing Techniques in Mission Planning

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ABSTRACT

This lecture paper addresses issues related to the major concern stated in Section 5.1 of the AGARD Advisory Report 313 "Mission Planning Systems for Tactical Aircraft (Pre-Flight and In-Flight). "A major concern involving all aspects of mission planning systems is the tremendous computational burden that is required for a wide variety of mission planning functions." The approaches for solving the Mission Planning Problem can generally be grouped into two categories: approaches that guarantee optimality and heuristic approaches that do not. Useful solution methodologies can be characterized by polynomial running time complexity. This paper concentrates on *computational* issues that arise when using *hierarchical decomposition* to solve the Mission Planning Problem. An analytic methodology and sample analyses are presented for an abstract planning system.

1. INTRODUCTION

This lecture paper addresses issues related to the major concern stated in Section 5.1 of the AGARD Advisory Report 313 "Mission Planning Systems for Tactical Aircraft (Pre-Flight and In-Flight). "A major concern involving all aspects of mission planning systems is the tremendous computational burden that is required for a wide variety of mission planning functions."

This paper concentrates on *computational* issues that arise when using *hierarchical decomposition* to solve the Mission Planning Problem. The hierarchical approach avoids monolithic (i.e., solving the problem as a single entity) limitations by decomposing the problem into a number of sub-problems, arranged in a hierarchy. [1] The top-level sub-problem is a scheduling problem over the entire problem range (or *horizon),* but with a small degree of detail. The middle-level sub-problems are over smaller problem horizons with a greater degree of detail. The bottom-level sub-problems are over the shortest horizon with the greatest level of detail. Once the initial planning problem is decomposed into these sub-problems, the sub-problems are solved and their solutions are combined to obtain the final solution.

A body of literature exists on the hierarchical formulation of planning problems but the theory is not developed enough to provide suitably accurate solutions for detailed real-world models. Thus, hierarchical application design is often driven more by implementation issues than theoretical justification. Consequently, this paper focuses on identifying *computational* issues relevant to the successful real-time *implementation* of general hierarchical planning applications. The ideas in this paper have been applied to planning Space Station Freedom activities. [4]

This paper deals with work-in-progress and is presented at an abstract level. Further work is needed to bring the full power of the methodology to bear on specific solution technologies for the Mission Planning Problem. Even so, valuable insight can be gained from the methodology when used to evaluate alternative mission planning system architectures.

2. BACKGROUND

2.1 Approaches

The approaches for solving the Mission Planning Problem can generally be grouped into two categories: approaches that guarantee optimality and heuristic approaches that do not. Optimal approaches have an advantage over heuristic approaches in that they are guaranteed to generate optimal solutions; however this performance advantage comes at the cost of much greater computational requirements for all but the least challenging problems. There are five classes of methods for generating optimal solutions to the Mission Planning Problem:

• *Complete Enumeration.* The simplest method of obtaining an optimal solution to the Mission

Presented at an AGARD Lecture Series on 'New Advances in Mission Planning and Rehearsal Systems: October 1993.

Planning Problem is to evaluate every possible mission plan, keeping track of the best solution. This approach is of course, completely impractical for all but the smallest problems as the solution time grows exponentially with problem size.

-*Dynamic Programming.* This approach generates optimal solutions faster than exhaustive enumeration. However, the solution times required by dynamic programming still grows exponentially (albeit less quickly than complete enumeration) with problem size.

•*Mathematical Programming.* As with dynamic programming, mathematical programming approaches generate optimal solutions faster than using complete enumeration, but the time to solution can still grow exponentially with problem size.

•*Gradient Methods.* Gradient methods are useful for solving optimization problems that have well behaved utility functions. Gradient approaches have particular difficulty for utility functions that contain large numbers of local maxima (which is the case for the Mission Planning Problem) as they tend to converge on and become trapped in the local maxima.

•*Newton Methods.* Newton methods use second derivatives (or the Hessian matrix for multi-variable functions) to improve upon gradient methods. These approaches are useful for certain types of optimization problems that have well defined utility functions, but are otherwise difficult or in some cases impossible to use, as is the case for the Mission Planning Problem.

In addition to optimal techniques, there are a variety of sub-optimal heuristic approaches for solving the Mission Planning Problem. Following are four representative classes of sub-optimal methods:

•*Heuristic Search.* The use of heuristics to solve otherwise intractable combinatorial optimization problems has become widespread in both the engineering and operations research communities. Heuristics are strategies, ideas, rules, guidelines, procedures, recipes, or methods used to guide a search toward the optimal solution within the solution space. Heuristics exploit knowledge about the specific problem domain to intelligently guide the search, so that near-optimal solutions can be generated in a fraction of the time that would be required to generate optimal solutions.

•*Neural Networks.* The application of neural networks to the solution of optimization problems [5] appears to have a variety of interesting applications, among which is the solution of combinatorial optimization problems. In spite of its novel perspective, however, the Hopfield approach to the solution of these problems is limited by its inability to find global minima with a single invocation of the algorithm. It is effectively a steepest descent procedure that settles at the nearest local minimum. Global minima are achieved only by initializing the algorithm at a sufficient number of different starting points. The primary difficulties of using neural networks to solve optimization problems are: adapting the networks to solve constrained optimization problems; and mapping complex optimization problems into neural network representations.

•*Simulated Annealing.* Simulated annealing is a statistical method developed by Kirkpatrick **[6]** for solving optimization problems. By itself, simulated annealing is too slow to provide real-time solutions to the Mission Planning Problem; however, this technique can be combined with other techniques to improve a planner's performance.

•*Expert Systems.* An expert system is a collection of rules, along with a procedure for using the rules to generate satisficing solutions to a wide spectrum of problems. The rules are generated by human experts in the problem domain; therefore expert systems are somewhat similar to heuristic methods. The primary difference between the two is one of implementation. Heuristic search techniques tend to be algorithmic, while expert systems are implemented using inference engines (e.g., forward or backward chaining) that operate on a rule base. Expert systems find solutions that are consistent with the rules, but do not necessarily search for optimum solutions.

In the end, all useful solution methodologies can be characterized by polynomial running time complexity; see the next section for details.

2.2. Complexity

One of the major problems in the implementation of many of the operations research and **AI** techniques discussed above involves the running time of the solution algorithms. In fact, algorithm running time is so important that the field of *computational complexity* has been developed to address this issue. Determining the running time of an algorithm has important considerations in problem implementation, problem size and computational resources. For example, no matter how fast a computer system, there are certain classes of algorithms that have been proven to be computationally intractable for the vast majority of inputs. This section is dedicated to explaining the basics of this theory and its relevance to the planning problem.

In computational complexity, an abstraction is made that when determining the complexity of an algorithm, it is only the rate of growth of the running time that is significant. [7] In addition, for most inputs only the leading terms of a running formula are considered. For example, suppose an algorithm designed as an insertion sort has a running time proportional to a quadratic function, $an^2 + bn + c$, where n is the number of inputs. Thus, for large n only the leading quadratic term is significant and the algorithm is defined to have a worst case running time of $O(n^2)$, where O() is the traditional notation for the ***order*** of a function. One algorithm is considered more efficient than the other if the running time has a lower order of growth. For example, an algorithm that runs in $O(n^2)$ time is more efficient than an algorithm that runs in $O(n^3)$ time.

The above example used a polynomial-time algorithm where the running time is proportional to $O(n^k)$ for some constant k. There are also algorithms that have running times that grow exponentially in the size of the input, represented as $O(c^n)$ for some constant c. Note that for large n, polynomial-time algorithms are much more efficient than exponential algorithms. Even though an exponential algorithm can outperform a polynomial algorithm for small n, for most inputs the increase in running times for exponential-algorithms quickly overwhelms the polynomial-time algorithms.

This distinction is so important that a problems have been classified as to whether they have solution algorithms that are of polynomial complexity or exponential complexity. All problems that have polynomial-time (also called *efficient*) algorithms are members of the class P. **A** problem is in class NP if a proposed solution can be checked for correctness with a polynomial-time algorithm. The class NP contains the class P (since class P algorithms can check a solution simply by generating it) as well as problems that have no known polynomial-time algorithm to obtain a solution. The next question then, is NP=P? [8]

Although this remains an open-ended question, there are a number of results that point to the fact that $P \neq NP$. For example, there exists a class of problems that are known as NP-complete. These problems contain no known polynomial time algorithm to find a solution Furthermore, it has been shown that if a polynomial-time algorithm exists for one problem in the class NP-complete, than a polynomial-time algorithm exists for all of the problems in this class. After a number of years of research, no polynomial-time algorithm has been discovered to solve any NP-complete problem.

There exists yet another class of problems, called NP-hard problems. Where as NP-complete problems must be formulated so that they only give yes-no answers, NP-hard problems can be formulated so that they give *any* required result, for example the lowest valued solution to an optimization problem. NP-hard problems have been shown to be at least as hard as the NP-complete problem. Moreover, an important result in planning theory is that most general planning problems belong to the class NP-hard [9]. Therefore, there are likely to be no polynomial time algorithms to optimally solve the general scheduling problem. Consequently, it seems useful **to** concentrate efforts on polynomial *approximate* (sub-optimal) solutions and heuristic techniques to obtain a solutions, rather than attempting to find optimal solution methods. This is exactly the approach of hierarchical planning and the focus of this paper.

3. ISSUES IN HIERARCHICAL PLANNING

The motivation of this paper is to examine implementation issues of hierarchical mission planning systems. **A** large amount of literature exists on the theory and applications of individual elements of a hierarchical system and there is a good deal of research on the theoretical aspects of this approach. [3] However, the work done so far has suffered in a number of different aspects. First, there are no detailed theoretical models for hierarchical planning systems with more than two stages. Second, the issue of feedback and replanning has not been explored in much detail, and third, there are no good, general models for systems characterized by uncertainties. [10] This section will discuss *implementation* issues for a general planning system by providing a precise framework for discussing issues of hierarchical planning. Once the framework has been developed and the issues are identified, models will be developed to examine some of the tradeoffs, advantages and disadvantages of different hierarchical concepts. **A** specific application of hierarchical planning to the Mission Planning Problem is found in [1].

3.1 The Hierarchical Planning Process

The *monolithic* planning problem consists of a single large problem where a number of variables must be specified so that certain limitations, such as precedence constraints and resource allowances, are satisfied. The monolithic problem is traditionally solved by a single large algorithm, which tries to examine all factors at once. Hierarchical decomposition decomposes the monolithic problem into a number of hierarchically arranged smaller sub-problems, thereby reducing the size of each problem. The actual problem decomposition is performed by either reducing the problem's range, (also called the problem *horizon)* or by reducing the problem's degree of detail. Thus, the top level sub-problem consists of the whole problem range, but only requires a small degree of detail. Consequently, the bottom level sub-problems schedule over a very short horizon but with a high level of detail.

The implementation of a hierarchical solution can be developed by designing hierarchically arranged groups of algorithms, which are defined as *nodes* or *objects*. Each of these objects must perform two separate functions. The first function is to decompose the problem by horizons into smaller, more detailed sub-problems that are sent off to nodes lower levels. The second is to schedule part of the problem over the node's specified horizon. This problem decomposition continues until the very lowest nodes, which solve the given problem with sufficient granularity. See [1] for the application of hierarchical decomposition to the Mission Planning Problem. The graphical representation of the structure formed by this process is a directed acyclic graph, or *tree.* (See Figure 3-1.)

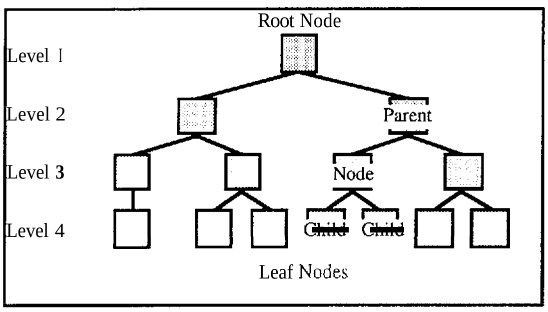

Figure 3-1. The hierarchical planning process structure. Each node represents a functional group of algorithms that perform two functions -- decomposition of a problem and solution of a sub-problem. The terminology that will be used to discuss the structure appears on the figure.

The terminology that is used to describe this hierarchical structure of objects is borrowed from graph theory and is defined as follows: the graph is considered to consist of a number of *tiers* (or *levels)* such that an object can only communicate with one object in the tier above it. Each object in the graph is defined as a *node*. The *root node* is defined as a single object at Tier 1. The *leaf nodes* are the objects in the last tier of the hierarchy. Each node can have a *parent,* defined as the object connected to it in the previous level, and a number of *children,* which are the objects connected to it on the lower tier.

The generic planning framework behind the analysis presented in this paper is illustrated in Figure 3-2. In this example, the structure has three tiers, where each node has exactly two children. The hierarchical planning process begins when the original planning problem is initially received by the root node. This node decomposes the problem with a *management algorithm* into several sub-problems. The management algorithm performs this problem decomposition by separating along problem *horizons*. That is, the root node management algorithm separates the initial problem into a planning problem to be solved over the entire problem horizon with a low level of detail, and two smaller problems to be solved over a shorter horizon with a higher level of detail. The (low level of detail) planning problem is solved at the root node by a *planning algorithm,* while the two shorter-horizon sub-problems are passed on to the child nodes. The management and planning algorithms take some finite amount of time to complete and yield solutions that perform at some fraction of optimal.

The two child nodes repeat the root node process by also solving a planning problem and sending sub-problems with shorter horizons to leaf nodes. The leaf nodes need not perform any management functions, they simply use planning algorithms to solve the problem. Finally, the sum of all the individual planning algorithm solutions yields the solution to the original problem, which is passed on to the control system to be implemented.

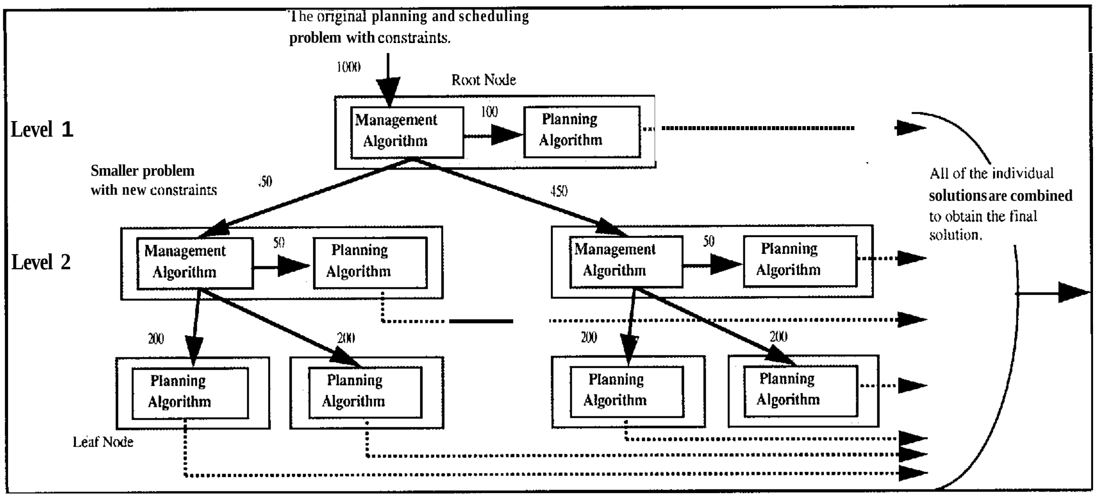

Figure 3-2. A framework for discussing the hierarchical planning process. The initial problem is received by the root node. The management algorithm decomposes this problem into three smaller problems — the first problem is solved by the root node's planning algorithm, while the second two problems are solved by the child nodes. This process is repeated until the lowest level. Finally, the individual solutions are combined to obtain a final overall solution. Hypothetical problem sizes are illustrated.

In addition to this basic system there are two additional issues that must be discussed. The first is the effect of resource passing — the type and amount of resources allotted by a management algorithm for the sub-problems. By utilizing models to predict the resources for children, the possibility arises that the passed resources may not yield sub-problems with feasible solutions. In this case, the child node must notify the parent of this inconsistency and the parent node must reformulate the problem in an attempt to achieve a solvable sub-problem for the child. If the system resource margins are consistently too tight then the overall system will take much longer to formulate a solution, since the system will constantly be replanning. On the other hand, if the resource margins are set too *loose* the solution obtained will be too far below optimal since there will be a surplus of unused, over-predicted resources.

The second issue that must be addressed is the effect of unpredictable events and failures. In a typical planning system unforeseen information may invalidate or, more likely, reduce the effectiveness of a plan. One way to counteract this effect is by replanning, i.e., resolving the plan based on new constraints and information. In the hierarchical system, any node may, at any time, decide to replan by generating a new plan using new and updated information. Note that replanning not only affects that particular node, but also all of the nodes descendants since new sub-problems must be reformulated.

In summary, the basic planning system framework generates plans by breaking the problems into sub-problems, dealing with each in varying degrees of detail. Each node breaks down the problem into smaller sub-problems with new resource margins. Each sub-problem is passed down to a child node and the process is repeated. The newly formulated sub-problems may or may not have feasible solutions, depending on the accuracy of the higher level planning models. In addition, the system attempts to achieve the best possible plan by replanning at any point in light of new information. The ultimate goal of the hierarchical process is to develop a robust system that can provide feasible, near-optimal schedules in real time and in the face of uncertainty and variability.

3.2 Implementation Issues in Hierarchical Design

The previous discussion of the hierarchical process introduced a number of different issues that must be considered when designing and evaluating a hierarchical planning system. This section identifies each of these issues and explores them in more detail.

3.2.1 Algorithmic Abstraction

The hierarchical planning process can be thought of as a connected group of algorithms. Consequently, it is necessary to note the most important features of these algorithms with respect to the hierarchical process. The two characteristics of an algorithm that will be examined here are *complexity* and *optimality*.

Each algorithm has the goal of obtaining a solution to a given problem. If there is at least one solution to the problem that satisfies all constraints, then the problem is classified as *feasible*. If the algorithm obtains a solution, then an objective function is applied to obtain a measure of performance, with respect to the algorithms optimality. Furthermore, if the solution is evaluated to be the maximum of an objective function, then the solution is considered *optimal* with respect to that objective function. Often, if enough is known about the algorithm and the types of problems that it is expected to solve, the performance of the algorithm can be measured and predicted. This question of optimality and performance is of prime importance when discussing the quality of algorithmic solutions, and plays a large part in the evaluation of a hierarchical system.

A general mathematical programming planning problem is to specify a number of variables, such that certain constraints are satisfied and an objective function is maximized. More precisely, the problem is the following;

$$\text{Maximize } z(\mathbf{x}) \qquad \text{(3-1)}$$
$$\text{Subject to } g_k(\mathbf{x}) \le \mathbf{b} \quad \text{for all } k$$

Where $\mathbf{x}$ = the tasks to be scheduled
$\mathbf{b}$ = the vector of resources assigned to a sub-problem
$z(\mathbf{x})$ = the objective function
g_k = the problem constraints

The traditional measure of an algorithm's performance is measured along two dimensions. The first is the running time of the algorithm, which will be discussed at some length below. The second is the ratio of the algorithms solution, $z(\mathbf{x}')$, to the optimal solution to the problem, $z(\mathbf{x}^*)$.

Obtaining near-optimal feasible solutions is not the only issue of importance when examining algorithms. Another important factor to consider is the algorithms running time, or ***complexity.*** For example, an algorithm might always discover an optimal solution, but it might take hours, days or even years to complete. This issue is particularly important in terms of the planning problem since the task of optimally solving the general planning problem belongs to the class NP-complete. Therefore, only an exponential algorithm can be guaranteed to derive an optimal solution. Exponential algorithms are inefficient for most inputs since they quickly become computationally intractable as the problem size increases.

Because there is such a dramatic increase in the running times for algorithms of exponential order, the hierarchical methodology described in this paper assumes that all algorithms will have running times of polynomial order. Accordingly, the solutions obtained are not guaranteed to be optimal. However, if the algorithms are well designed, the solutions can be quite close to optimal. The question of just how close a polynomial approximation algorithm comes to being optimal is an issue that is problem dependent and must be carefully explored.

3.2.2 Exploiting Computational Complexity

In the previous section the assumption was made that only algorithms with polynomial dependency will be examined. One of the great advantages of the hierarchical scheme is that by breaking the problem into smaller parts the polynomial complexity of the scheduling algorithms can be exploited to reduce the computation time of the entire solution. By making the assumption that each of the hierarchical planning algorithm complexities are less than the monolithic algorithm complexity, this notion can be captured in the simple mathematical expression:

$$\sum_{i=1}^{j} (x_i^{c_i}) < \left(\sum_{i=1}^{j} x_i \right)^c \qquad \text{(3-5)}$$

Where:

x_i = the size[1] of sub-problem i
c_i = the complexity of the hierarchical algorithm for sub-problem i
c = the complexity of the monolithic algorithm

And;

$$\sum_{i=1}^{j} (x_i) = \text{the total size of the problem}$$

$$c_i \le c \text{ for all } i$$

The assumption that c_i is less than or equal to c is a reasonable one, considering that one of the goals in designing the hierarchical system is to reduce the complexity of the sub-problems.

In addition to this combinatorial advantage, additional savings can be achieved by solving sub-problems in parallel since problems within a level

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1 The size of a problem can be thought of as the number of bits in a digital representation of the problem.

are independent. Consequently, the sub-problems can be solved independently on individual machines. The final result is a reduction in running time that can be extremely large. However, this saving must be carefully examined in light of the additional communication, management and overhead costs that must be assumed when adopting a hierarchical planning scheme.

3.2.3 Problem Decomposition by Horizon

Another important issue in implementing the hierarchical design is deciding upon how the initial problem will be divided into sub-problems. In the general hierarchical system, problems are decomposed according to problem *horizon*, where the horizon is defined as the appropriate range of the problem. Typically horizons for problem decomposition is *temporal* or *spatial*, where the problem is broken down by units of time or distance. In temporal decomposition the root node *management* algorithm would examine the problem over the entire mission time, sending its children sub-problems with shorter temporal or spatial horizons to be solved in detail. Then, the root node *planning* algorithm would then solve the planning problem over the entire problem horizon with a coarse level of detail. See [1] for specific application of this to the Mission Planning Problem.

3.2.4 Probabilistic Events and Replanning

Mission planning systems face unpredictable events. For example, the health of the vehicle or external conditions might change unexpectedly. Thus, any plan developed with less-than-perfect knowledge of the world will be affected as unforeseen events occur. Just how much a plan is affected depends on the predictability of the world and the probability of the unforeseen events. In addition, if the plan's solution is robust enough, then changes in the environment affect a plan's *optimality* rather than its *feasibility.*

One way to deal with imperfect knowledge about the world is to *replan* as often as possible. By replanning immediately, new information and developments can be considered as soon as they start to affect the plan's performance. In a hierarchical planning decomposition, replanning can take place at any node in any level. This often serves to localize the effects of unforeseen events and allows the events to be handled as swiftly as possible. To obtain the best system performance, there must be a balance struck between how accurate plans remain, how long it takes to formulate a new plan and the frequency of replanning. Consequently, a system with a large number of unforeseen events would require a higher frequency of replanning than a system with a relatively low number of unforeseen events since plan performance is being degraded more rapidly.

3.2.5 Management and Communication Overhead

When dealing with a hierarchically distributed problem, there exists an important issue in deciding how the nodes should be *managed,* where managing is defined as the controlling and monitoring of the planning process. Each node in the hierarchical structure actually consists of two parts; a *planning management algorithm* and a *planning algorithm.* The planning management algorithm effectively manages both the planning process and the execution of the plans by decomposing sub-problems, monitoring plan progress, monitoring replanning appropriateness, logging unforeseen events, determining appropriate planning algorithms and controlling interactions between lower and higher levels of the hierarchy. The planning management functions also act as an interface between other systems such as control, fault detection and isolation, redundancy management, navigation and other onboard systems. On the other hand, the planning algorithms simply generate a plan based on the problem and resources assigned to it. See [1] for more detail.

Management functions can be considered overhead, since they do not perform any plan functions. However, they are not the only type of overhead assumed when implementing a hierarchical system. For example, there are costs assumed with communication of resources and problems among nodes. This communication cost, combined with the management functions necessary to divide and formulate sub-problems can greatly increase the complexity of the hierarchical problem and can make the solution method undesirable.

3.2.6 Resource Margin Optimization

Another variable in the hierarchical planning scheme is the type of *resource margins* that are passed from higher levels to lower levels. Resource margins are a measure of the amount of resources a parent node passes to child node in order for the child node to complete its problem. Since the higher levels can only operate on models that approximate how the lower levels will formulate their plans, there is a probability that a parent node might send a child node a sub-problem that is infeasible.

The probability that a sub-problem is infeasible is higher if the parent node has a relatively *tight* model which predicts that the lower level will require a fewer number of resources than a *loose* model will. On the other hand, if the higher level uses a loose model that over predicts the number of resources, the system runs the risk of under utilizing resources and may obtain a solution that is far from optimal. Thus, a balance must be struck between the solution requirements, the time it takes to generate a solution and resource margin settings.

3.2.7 The Hierarchical Structure

Finally, the last issue to consider is the actual structure of the hierarchical solution. Certainly, it is very important to consider such issues as how many levels should exist, how many nodes belong should be on each level and how they should be interconnected. Deciding upon the structure of the planning solution is implementation dependent and dependent upon such things as computational resources, communication bandwidths and problem models.

3 3 Analysis of Hierarchical Systems—Two Models

There are a number of issues to be considered when developing a hierarchical system. What are the most important issues that must be considered? How tight should the resource margins be made? What structure should be used? What is the balance between optimality and replanning? These and many more questions must be answered before designing and implementing a hierarchical system. One good way to answer these questions is to develop *models* of the hierarchical planning process. By examining these models valuable insight can be gained into the answers of important hierarchical questions.

There are essentially two types of models that can be used to answer these questions. One model is the *analytical* type consisting of mathematical formulas that model the planning process. The formulas are then solvable using mathematical techniques. These models are useful, since the exact state of the system can be determined at any point in time. Analytical models also have the advantage of allowing a rather detailed analysis of all the model parameters. However, analytical models tend to oversimplify the system to obtain a solvable analytical formulation. Another type of model that addresses these issues is the *simulation* model, which simulates the planning process by probabilisticly modeling the behavior of the system over time. [11]. This has the advantage of closely representing the planning process, but does not lend itself to easy analysis.

This lecture paper describes an analytical model; for an example of a simulation model, see [4].

4. THE ANALYTICAL MODEL

The analytical model captures the hierarchical planning process by representing planning *performance* with mathematical functions. The hierarchical planning system can then be analyzed by varying the function input parameters and exploring their effect on performance. In order to further develop understanding, the hierarchical schedule performance is compared against a centralized, monolithic planning system.

One of the key points of the analytical model is that issues are examined according to how they effect system *performance*. System performance in the analytical model is defined as the rate at which elemental "tasks" in the plan are executed and is measured as a ratio of the *actual* rate of task execution to the *desired* rate of task execution. Thus, this performance metric measures the difference between plans that schedule different numbers of events. There are some problems in choosing this definition of performance. Most obviously is the fact that completion of some tasks has a greater effect on plan performance than the completion of other tasks. This occurs when tasks have a greater intrinsic value or if the tasks completion has valuable consequences for other tasks. Thus, what is of prime importance is not the raw number of tasks that are scheduled but rather the combined value of the tasks. Nevertheless, if it is assumed that tasks with greater importance are scheduled first, or if all tasks have equal value, then this metric is a reasonably accurate proxy for the "real" value of a plan.

In terms of the eight issues identified in Section 3.2, the analytical design models them as follows.

**Algorithmic Abstraction.* Complexity within the analytical model is explicitly modeled using the polynomial algorithm assumption, thereby allowing modeling of running times. The performance of the algorithms is modeled as the *rate* in which tasks are initiated.

**Exploiting Computational Complexity*. The analytical model assumes a system of connected independent hierarchical processors, each running algorithms of known computational complexity. Therefore, the polynomial complexity exploitation issue is fully modeled.

• *Problem Decomposition by Horizon.* Problem decomposition is explicitly modeled as a user-defined variable specifying the fraction of the problem that is passed from level to level. The problem horizon is defined as temporal and contributes to the actual size of the problem. The time horizon exists as a user-defined variable. Other problem size variables are also configured by the user.

•*Management and Communication Overhead.* Management overhead is modeled as an algorithm that acts to decompose the problem and determine new resource margins. The algorithm is assumed to be of polynomial complexity and the degree of the polynomial can be set. Communication and other overhead is simply modeled as a linear factor that is applied directly against system performance.

-*Probabilistic Events and Replanning*. Uncertainty in the environment is modeled by a degradation in the performance of the plan over time. Plans are assumed to have a halflife, i.e., the length of time it takes for a plan to degrade to half of the original value. Replanning occurs as soon as a plan is generated, using new information that is acquired during plan formulation.

-*Resource Margin Optimization* is implicitly modeled as a fraction of the problem that must be returned from a lower level node to a higher level node. By specifying the percentage of the problem that is sent back, a relative measure of resource margin tightness can be modeled.

•*The Hierarchical Structure* is constrained to only three levels -- the minimum amount of levels needed capture the essence of hierarchical behavior. This is without loss of generality, since all three types of nodes are modeled -- nodes without parents, nodes without children and nodes with children and parents. In addition, there may be any number of nodes in each of the lower levels to allow flexibility in exploring the effects of structure.

4.1 The Model

This section provides a detailed description of the analytical model and is divided into four separate sub-sections. The first sub-section outlines the basic methodology used in developing the analytical planning model by formulating a *basic model.* The next two sub-sections detail the changes to the basic model for the hierarchical and the monolithic model, respectively. The final sub-section provides a summary of the analytical model by explaining some of the typical output graphs.

4.1.1 The Basic Planning Performance Model

To use analytical functions to model the performance of the planning process, the first assumption must be that the system performance is in a steady state over some period of time. That is, the system is in a cyclic pattern so that performance can be predicted at any point in time with analytical formulas. In the paragraphs that follow, a detailed explanation of the basic model of the planning process is described.

Before the analytical functions can be determined, a utility measure must be defined to compare the relative worth of different types of plans. In an attempt to define such a utility measure, the notion of *value* has been introduced. Value is defined as a linear function of the rate at which elemental tasks of the plan are being initiated. For example, a plan that initiates 1000 tasks an hour has twice the value of a plan that initiates only 500 tasks per hour. (This assumes that it is valuable to actually have the 1000 tasks performed.) Value acts as the main indicator of a plan's overall effectiveness and is measured as a ratio between the tasks being performed and the optimal number of tasks that could be performed, where the optimal number of tasks is derived from the optimal solution to the planning problem. Thus, the ratio (as a percentage) can be determined for the plan at any point in time. For example, the performance of an ideal plan would be represented as the constant function $f(t) = 1$. A plan that only initiates half of the optimal tasks would have system performance equivalent to the function $f(t) = 0.5$.

Plan values are not constant over time. As time progresses, the value of the plan decreases as unforeseen events occur and certain tasks can not be initiated. This new information degrades the original plan performance by forcing the removal of lower priority events. Until this new information can be considered and a new plan generated, the overall performance will be adversely affected. This uncertainty is analytically modeled in the application as a degradation of plan value, so that tasks are initiated at a slower rate as time progresses. The degradation of the value is modeled as a simple exponential halflife function which initially begins at 100% and drops to 50% when t = half-life.

$$v(t) = e^{-\alpha t^2} \quad (4\text{-}1)$$

Where:

$v(t)$ = plan value as a function of t
t = time in hours
$\alpha = \frac{\ln(2)}{t_{hl}^{2}}$
t_{hl} = half-life of the plan in hours

For example, Figure 4-1 shows the value of Equation **4-1** function with the half-life equal to five hours over a time ranging from 0 to 25.

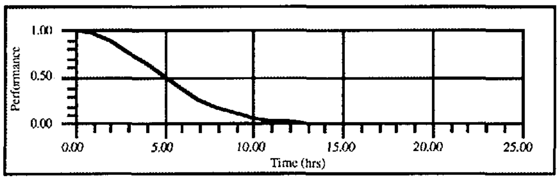

Figure 4-1. Performance of a theoretical plan over time, t = (1..25), half-life = 5

However, this is not an accurate representation of plan performance for either the hierarchical or monolithic system. First, note that this assumes the plan has already been generated. This notion will be addressed later in this section when initial conditions and transients are discussed. Second, the hierarchical process replans in an attempt to account for unforeseen events. To model this replanning the analytical system generates a new plan as soon as the old plan takes effect. The graph of the plan value can be better represented as the following. Note that the mod(number,divisor) function represented is simply the standard modulo function which returns the remainder after the number is divided by the divisor.

$$v(t) = e^{-\alpha * \mathrm{mod}(t, t_{rpln})^2} \quad (4\text{-}2)$$

Where:

$v(t)$ = plan value as a function of t
t = time in hours
t_{rpln} = time in hours it takes to generate a new plan
$\alpha = \frac{\ln(2)}{t_{hl}^{2}}$
t_{hl} = half-life of the plan in hours

Figure 4-2 shows this function with halflife equal to five hours and the replan time equal to ten hours.

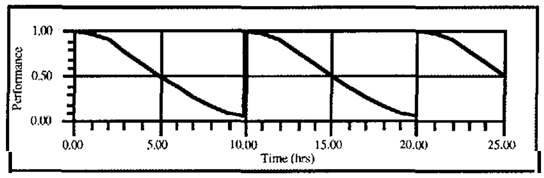

Figure 4-2. Performance of a theoretical plan over time t = (1...25), half-life = 5, replan time = 10

Now, the next task is to determine how to calculate the time it takes to solve the planning problem. Essentially, this means estimating how long it would take to run a particular planning algorithm given a problem of certain size. Certainly this is a function of the problem size, the complexity of the scheduling algorithms utilized and the computer resources available. The method or computing the replan time is adopted from [7] and is given by:

$$t_{rpln} = \frac{n_{ps}^{c}}{p*10^6*60*60} \quad (4\text{-}3)$$

Where:

t_{rpln} = time in hours it takes to generate a new plan
n_{ps} = the size of the problem to be solved
c = the complexity of the planning algorithm
p = the performance of the computer in millions of instructions per second (MIPS)

The problem size itself can be considered as a function of the length of time for which to plan (time horizon), the .number of variables involved in each decision and the number of decisions per hour. The result is a representation of problem size, which can be given by the following formula.

$$n_{us} = t_{hzn} * v * d \quad (4\text{-}4)$$

Where:

n_{ps} = the size of the problem to be solved
t_{hzn} = total planning horizon in hours
v = number of variables per decision
d = number of decisions per hour

Finally, the problem size is divided by the computer performance to obtain the actual replan time. The computational speed is the MIPS (Millions of Instructions Per Second) rating of the computer used to solve the problem. The final result is the number of hours it takes to execute the planning algorithm

4.1.2 The Hierarchical Model

The simplified model dealt with above is useful to convey the basic modeling paradigm used in the analytical model, but this simple model must be expanded to represent a hierarchical modeling scheme. The purpose of this section is to describe how the basic model is extended for the hierarchical system.

It is assumed, without loss of generality, that the hierarchical planning system is composed of three levels (or tiers) -- the minimum number of levels that maintains the hierarchical structure. While the *brunching factor* for each of these levels is free to change, the hierarchical system is constrained to exactly three tiers, where the branching factor is defined as the number of children to a parent. Finally, the analytical model represents the hierarchical architecture as a directed acyclic graph as shown in Figure **4-3.**

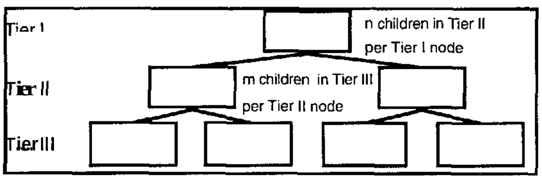

Figure 4-3: Hierarchical Decomposition in the Analytical Model

The communications between the tier nodes are modeled such that when a node first receives a problem, it breaks the task into smaller problems, sending some of the problems to lower levels, passing some of the problems back to the higher level and solving the rest of the problems. In addition, the management and planning phases are explicitly modeled. There is a management phase in which the problem is inspected and passed on to other nodes and a planning phase in which a portion of the problem is actually solved.

Using the basic analytical model discussed above, each node's performance is modeled as an repeating exponential function. That is, for each node j in tier i, the value at time t is given by:

$$v_n(i,j,t) = e^{-\alpha(i)*mod(t,t_{rpln}(i,j))^2} \qquad (4\text{-}5)$$

Where:

$v_n(i,j,t)$	=	the value at node j in tier i at time t
t	=	time in hours
$t_{rpln}(i,j)$	=	time it takes for node j in tier i to replan
$\alpha(i)$	=	$\frac{\ln(2)}{t_{hl}(i)^2}$
$t_{hl}(i)$	=	half-life of the plan in hours for tier i

To define the replan time for a node it is necessary to recognize that each node (except for the *leaf* nodes that have no children) must complete two tasks, the management phase and the planning phase. The total time *to* plan at each node is given by:

$$t_{rpln}(i,j) = t_{mng}(i,j) + t_{pln}(i,j) \qquad (4\text{-}6)$$

Where:

$t_{rpln}(i,j)$	=	time it takes for node j in tier i to replan
$t_{mng}(i,j)$	=	the time it takes for node j in tier i to compute its management functions
$t_{pln}(i,j)$	=	the time it takes for node j in tier i to compute its planning functions

From the discussion in the basic model it is known that the planning time is a function of complexity and computer speed and is given by:

$$t_{pln}(i,j) = \frac{n\ \mathrm{Ins}(i,j)^{c_p(i)}}{p(i)*10^6*60*60} \qquad (4\text{-}7)$$

Where:

$t_{pln}(i,j)$	=	the time it takes for node j in tier i to compute its planning functions
$n_{plns}(i,j)$	=	the planning size for node j in tier i
$p(i)$	=	the speed of the computer in tier i in **MIPS**
$c_p(i)$	=	planning complexity for tier i

The management time is also function of complexity and computer speed and is given by:

$$t_{mng}(i,j) = \frac{n_{mngs}(i,j)^{c_m(i)}}{p(i)*10^6*60*60} \quad (4\text{-}8)$$

Where:

$t_{mng}(i,j)$	=	the time it takes for node j in tier i to compute its management functions
$n_{mngs}(i,j)$	=	the management problem size for node i in tier i
$c_m(i)$	=	management complexity for tier i
$p(i)$	=	the speed of the computer in tier i in **MIPS**

The planning problem size is a function of the local planning horizon and is given by:

$$n_{plns}(i,j) = t_{lhzn} * n_{ns}(i,j) \quad (4\text{-}9)$$

Where:

$n_{plns}(i,j)$	=	the planning size for node j in tier i
t_{lhzn}	=	the local planning horizon
$n_{ns}(ij)$	=	the size of node j at tier i

The local planning horizon is simply an estimate of the length of time for which to plan. Naturally, the planning algorithms will concentrate only on this shorter local horizon. However, the management algorithms must have a more global planning view to best deal with the organizational flavor of the their problem. Thus, the management size is dependent on a global planning horizon. The management algorithm is also a function of the size of the problem which is actually passed down to the next tier, rather than the actual problem that remains at the node to be solved. Therefore, the management problem size is given by:

$$n_{mngs}(i,j) = tghzn * \sum_{j=1}^{m} n(i+1,j) \quad (4\text{-}10)$$

Where:

$n_{mngs}(i,j)$	=	the management problem size for node j in tier i
t_{ghzn}	=	the global management horizon
$n(i,j)$	=	the size of node j at tier i

Finally, the total problem size at any node is a function of the percentage of the problem returned and the percentage of the problem passed to the next level at each node.

$$n(i,j) = \frac{1}{1+r(i)+p(i)} * \left\{ \frac{p(i-1)n(i-1,j)}{b(i-1)} + r(i+1)n(i+1,j)b(i) \right\} \quad (4\text{-}11)$$

Where:

$n(i,j)$	=	the size of node j at tier i
$r(i)$	=	the percentage of the problem returned to tier i-1
$p(i)$	=	the percentage of the problem passed on to tier i+1
$b(i)$	=	the number of children (or branches) for a node at tier i
$n(0,j)$	=	v*d
d	=	decision per hour
v	=	variables per hour

Note that the actual replan time for a node is not independent of the other nodes. First, nodes must wait before they can process data. For example, Tier II nodes must wait for a problem from Tier I before they can proceed. Similarly, Tier III nodes must wait for a problem from Tier II before they can proceed. Second, nodes must wait after they have processed the data. For example, the Tier I node must wait for Tier II to finish it's processing before it can send another problem down. Similarly, Tier II must wait for Tier III to finish it's processing before sending another problem.

The actual concept is shown more clearly in Figure 4-4. There are a few important points to consider about this figure, which shows the activities of representative nodes in Tier I, Tier II and Tier **111.** First, note that no matter what the individual replan times for each tier, one tier's nodes will always be processing. Consequently, assuming that a node replans as often as possible, there is a *global **replan** time* that remains constant across all three tiers. This global replan time specifies the amount of time a tier's node must wait before proceeding. Therefore the node's idle time is determined by the longest running node in the system.

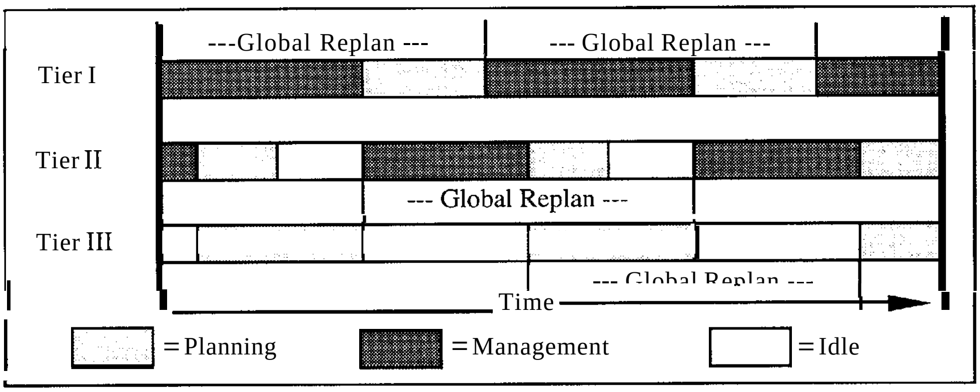

Figure 4-4. **A timeline** showing a snapshot at any point in time of the activities of representative nodes in Tier I, Tier II and Tier 111. Essentially, the idle time of the nodes in Tier II and Tier III is determined by the idle time of the node in Tier I, which takes the longest to complete. Thus, if every node replans as often as possible a notion of global replan arises -- the shortest time that any node must wait before it can replan.

Now that it has been determined how and when each node calculates and recalculates its plan, it is time to address the second issue; how will the complete plan value be represented from the smaller plans that are constantly being generated? In the analytical model, it is assumed that the total plan is a weighted sum of the plans generated at each node. In this way the contribution of the plan to the overall value is dependent upon the size of the problem. The plans generated at each tier are assumed to be identical. Therefore, in essence, the total plan value is given by:

$$v_{tot}(t) = \frac{\sum_{i=1}^{3} n_{ts}(i) v_t(i,t)}{\sum_{i=1}^{3} n_{ts}(i)} \quad (4\text{-}12)$$

Where:

$v_{tot}(t)$ = the total plan value at time t

$n_{ts}(i)$ = the size of tier i

$v_t(i,t)$ = the value of tier i at time t

The size of a tier is simply a function of the size of each of the nodes and is given by:

$$n_{ts}(i) = \text{sub}(i) \sum_{i=1}^{n} n(i,j) \quad (4\text{-}13)$$

Where:

$n_{ts}(i)$ = the size of tier i

$n(i,j)$ = the size of node j in tier i

$\text{sub}(i)$ = sub-optimality coefficient for tier 1

The value at a tier is also simply a function of the value's of the node's and is given by:

$$v_t(i,t) = \sum_{k=1}^{n} v_n(i,j,t) \quad (4\text{-}14)$$

Where:

$v_t(i,t)$ = the value of tier i at time t

$v_n(i,j,t)$ = the value of the plan of node j in tier i at time t

Note, there is no notion of replan time within this total value, since it is inherent from the global re-plan times discussed above.

There is one final variable that is introduced into the hierarchical model, which is called the *sub-optimality coefficient*. Naturally, there are many inefficiencies inherent to the system that have not been explicitly modeled. For example, there is certainly a communications cost between nodes that must be considered, There is also a cost in recombining the problem for separate sub-problems. There are also many inherent limitations such as system saturation and deadlock. Recognizing this shortfall, the sub-optimality coefficient is a variable that reduces a particular tier's plan value by a linear factor. The total effect will be an overall reduction in total plan value which represents non modeled events like those discussed above.

4.1.3 The Monolithic Model

The monolithic model is much simpler than the hierarchical model and closely resembles the basic plan model described above. One purpose of the analytical model is to *compare* both design methodologies. The variables defined for the hierarchical model were translated, to the extent possible, into the monolithic model.

To compare both design methodologies, the size of the problems must be similar. In the analytical model, the size of the monolithic model is assumed to be related to the hierarchical model in the following way;

$$n_{plns} = \sum_{i=1}^{3} \sum_{j=1}^{n(i)} t_{lhzn} * n(i,j) \qquad (4\text{-}15)$$

Where::

n_{plns} = the size of the planning problem in the monolithic model

t_{lhzn} = the local horizon

$n_{ns}(i,j)$ = the size of node j in tier i

$n(i)$ = the number of nodes in tier i

Essentially, the monolithic model must solve the same local-horizon *planning* problem as the sum of the parts of the hierarchical model, but without all of the management overhead inherent to the hierarchical model. This is not to say that the monolithic model does not perform any management functions. Indeed, the model again is split into two separate problems; a management problem and a planning problem. The size of the management problem is similar to the size of the hierarchical management problem and is given by:

$$n_{mngs} = t_{ghzn} * vars * decs \qquad (4\text{-}16)$$

Where:

n_{mngs} = the size of the management problem

t_{ghzn} = the global management horizon

vars = number of variables per decision

decs = number of decisions per hour

Finally, the replan time is very similar to the hierarchical model.

$$trpln = tmng + tpln \qquad (4\text{-}17)$$

Where:

t_{rpln} = the time it takes to complete the plan computation

t_{mng} = the time to compute its management functions

t_{pln} = the time *to* compute its planning functions

$$t_{pln} = \frac{n_{plns}^{\ c_p}}{p*10^6*60*60} \qquad (4\text{-}18)$$

Where:

t_{pln} = the time it takes to compute the planning functions

n_{plns} = the planning size

c_p = planning complexity

p = the speed of the computer in MIPS

$$t_{mng} = \frac{n_{mngs}^{\ c_m}}{sp*10^6*60*60} \qquad (4\text{-}19)$$

Where:

t_{mng} = the time it takes to compute the management functions

n_{mngs} = the management problem size

c_m = the management complexity

p = the speed of the computer in MIPS

Now that the replan time based on the problem size has been determined, it is a simple matter to use the value function to obtain the plan's value at any point in timet.

$$v(t) = e^{-\alpha * mod(t,rpln)^2} \qquad (4\text{-}20)$$

Where:

v = the value of the plan at time t

t = time in hours

t_{hl} = monolithic half-life of the plan in hours

t_{rpln} = time it takes to generate a new plan (hrs)

$\alpha = \frac{ln(2)}{t_{hl}^{\ 2}}$

There is only one final issue that must be discussed in the model design -- initial conditions. Naturally, when the system is first initialized, the value of the plan will be zero until the first plan can be generated. After this first plan is generated, the system will achieve a steady state since there will be residual value from the previous plan as the new plan is implemented. This causes "blips" in the performance chart as the initial transient conditions affect the performance.

4.1.4 Model Output

Typical model outputs are illustrated in this section. There are three types of output graphs that are illustrated; a performance line graph, a comparison bar graph and a timeline of node value. Consequently, there are eight charts that can be used to analyze the results: a line graph showing monolithic performance, a line graph showing hierarchical total performance, three comparison bar charts showing either MIPS usage or replan times for each of the levels and three timeline charts for node performance for each of the levels. Using these graphs, a rather detailed picture of system performance can be generated and examined.

Figure 4-5 shows outlines a plan's performance for a single node in Tier I. The top line chart graphs the plan performance versus time for that particular node. The timeline graph immediately beneath it shows the node state at each moment in time. Light gray corresponds to a node performing managing functions. Black represents a node performing planning functions. White represents the node idling -- waiting for information from either above or below. The timeline chart corresponds to the performance graph in that as soon as the node is finished replanning (the end of the black state) plan performance jumps to the highest value, where it immediately starts to degrade.

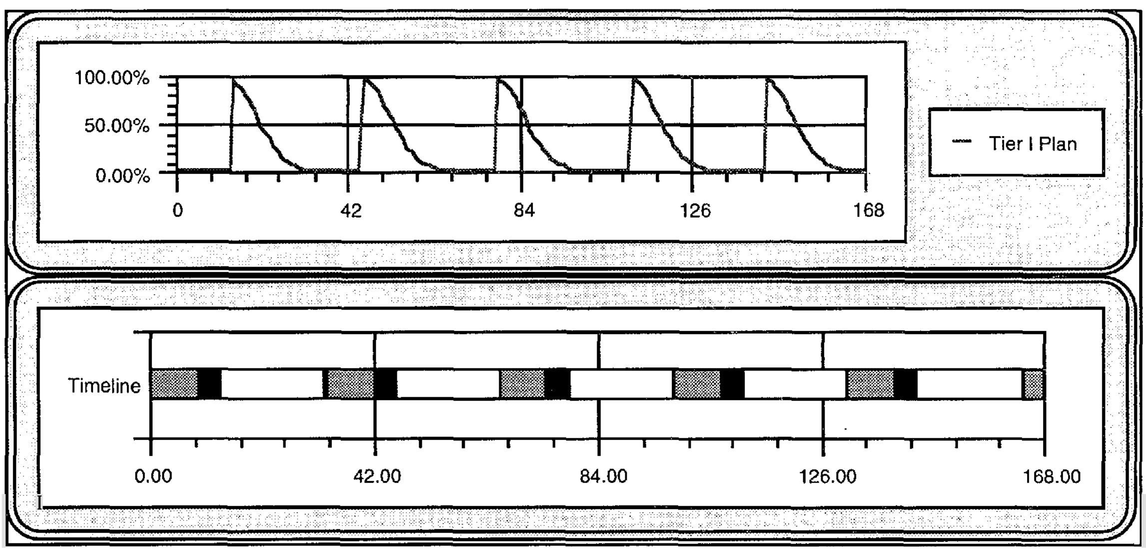

Figure 4-5. A timeline chart for a node in Tier I. The top graph shows the nodes plan performance over time, while the bottom graph shows a timeline of the nodes activities. These graphs can be developed for each tier in the system thereby providing a complete overview of the systems performance.

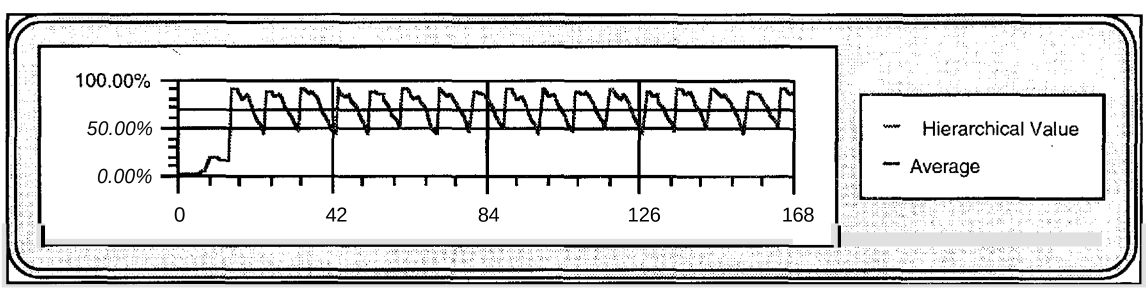

Figure 4-6. The individual tier nodes performance graphs can be combined into a measure of overall hierarchical system performance, which is shown here.

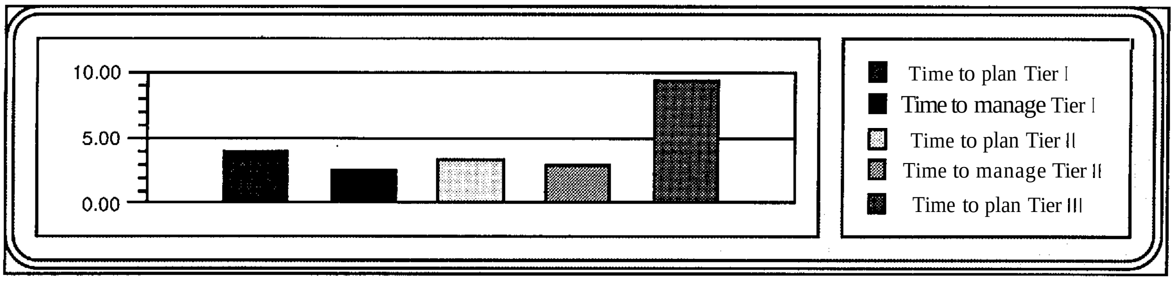

Figure 4-7 The replan times for each activity in the system. The replan times can be measured in an effort to pin-point potential bottlenecks in the system.

Figure 4-6 demonstrates a performance graph for the entire system over time. After start-up transients disappear, the system reaches a steady state of performance representing a weighted average of the performance of all the nodes in the system.

Finally, Figure 4-7 outlines the time it takes for each node in the hierarchy to perform one of its functions. For example, the time it takes for a node in tier III to plan is longer than any of the other times. This represents a system bottleneck. Plan performance can be improved by decreasing the time it takes to perform this function. This could be achieved by either increasing the speed of the computer in these nodes, or by decreasing the complexity of the planning algorithm.

In conclusion, all of the base variables that must be specified to define the system will be described. This list of variables shown in Figure 4-8 specifies the entire state of the model.

Hierarchical Parameters		Monolithic Parameters	
Halflife tier I tier II tier III	The halflife of the plan generated at each tier.	Halflife	The halflife of the monolithic plan.
Planning Complexity tier I tier II tier III	The complexity of the planning algorithm used at each tier.	Local complexity	The local complexity used for sizing the planing portion of the problem.
Management Complexity tier I tier II	The complexity of the management algorithm used at each tier	Global complexity	The global complexity used for sizing the management problem.
Computer Speed tier I tier II tier III	The speed of the computer used for each node in the tier.	Computer speed	The speed of the monolithic computer.
Fraction of Problem Passed tier I tier II	The fraction of the problem that is passed on to the next tier.	**Problem Size Parameters**	
Fraction of problem returned tier II tier III	The fraction of the problem that is retumed to the previous tier.	Number of tier N tasks per decision	The number of tasks per decision.
Planning horizon tier I tier II tier III	The local planning horizon used to size the planning problems.	Number of decisions per hour	The number of decisions per hour.
Sub-optimality coefficient tier I tier II tier III	The coefficients used to model communications and other overhead.	Time horizon	The mission time horizon.

Figure 4-8. The parameters that specify the entire state of the analytical model.

4.2 Results

The analytical model has been useful in identifying a number of key features about planning systems. The first is the effect of load *balancing*—designing a system so that the each node in the level is utilized as much as possible. The second important feature is the sensitivity to the complexity of algorithms. Even a relatively small change in the complexity of an algorithm can cause it to require large amounts of resources, thereby causing a system bottleneck. In addition, analytical results seem to indicate that the hierarchical planning process outperforms the monolithic scheme in all but the smallest cases. Even with the increased cost in communication and overhead, the algorithmic savings are notable.

The following sections outline some parametric analyses that were performed with the analytical model. Besides the points that were mentioned above, several other interesting features can be garnered from the studies.

4.2.1 Performance vs. Problem Size

The first analysis, show in Figure 4-9, deals with the effects of performance versus problem size for both the hierarchical and monolithic systems. First, note that the parameters were chosen such that the hierarchical and monolithic plan performances were equal when the relative problem size was ten. As the number of tasks is increased, the value of the plan performance naturally fell. What is important to note is that the hierarchical performance falls at a slower rate than the monolithic performance, indicating that in the face of increased loads the hierarchical system performs better. Note that this analysis was done with no load balancing. A system that is poorly balanced solves the problem with only a few nodes while all other nodes lie idle. A system that is well balanced has relatively few nodes lying idle at any one time. Since this analysis was done with no load balancing, the hierarchical system was not operating at peak efficiency. The reason that the increase in performance is not more dramatic is due to management and communication limitations inherent to the problem.

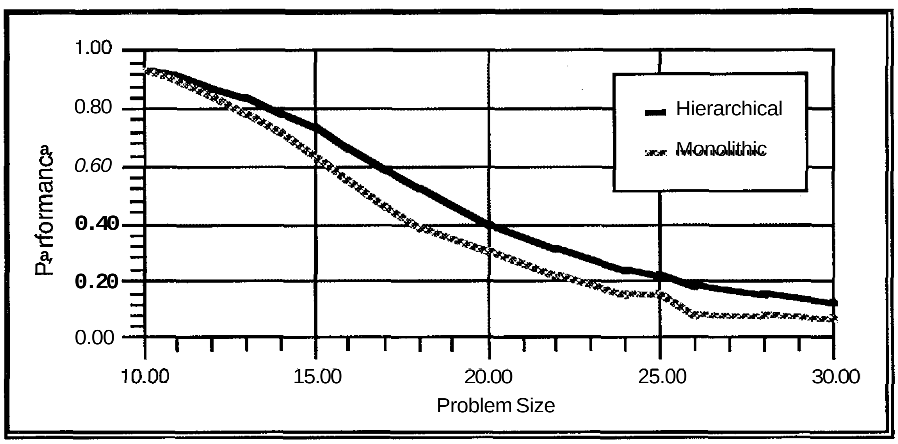

Figure 4-9. Hierarchical and monolithic performance as a function of problem size.

This performance advantage is made clearer in the next analysis, shown in Figure 4-10, which performs the exact same experiment, except with load balancing. This means that after the problem size was increased, it was redistributed across the nodes to improve performance. With load balancing the hierarchical system performs better under increased loads. This type of load-balancing could be implemented in an actual hierarchical system rather straightforwardly. For example, the planning system could monitor each of the nodes and dynamically redistribute the problem so that each node requires approximately the same time resources in order to solve the problem. Recall from Figure 4-4 that the global replan time is limited by the maximum of each tier's replan time. If this maximum can be shortened by making all of the replan times equal, there will be a corresponding increase in the plan value. This is exactly what is occurring here.

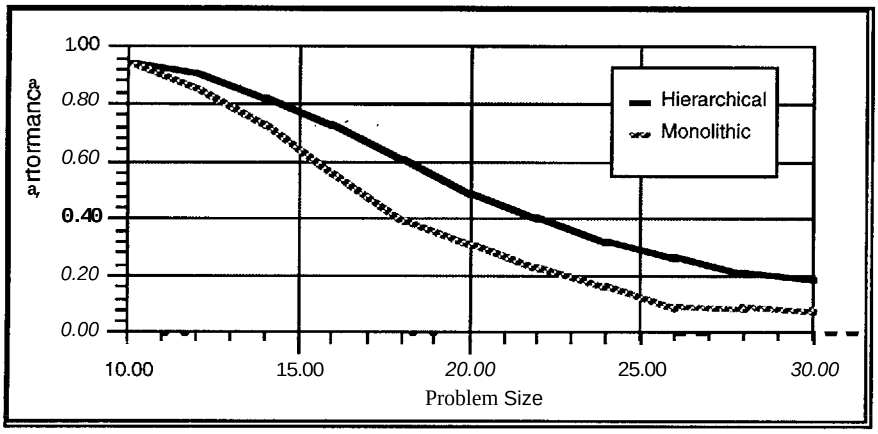

Figure 4-10. Hierarchical and monolithic planning performance as a function of problem size, with load balancing.

4.2.2 Performance vs. Computer Power

The next analysis, shown in Figure 4-11, deals with the absolute effect of computer power on the performance of the two systems. Computer power was increased and the performance of the system was measured. It is quite evident that the hierarchical system performs much better with far less raw computer power. With all other parameters equal, the performance of the distributed system quickly approaches optimal as overall computer power is increased, while the monolithic system performance remains extremely low. (The overall computer power was measured as the sum of the MIPS in each node.) This phenomena has an important effect on overall cost and feasibility, since it is easier to provide a large number of smaller computers rather than one large computer. The size of a large computer is not infinitely expandable, and is limited by available technology. The reason behind the computer power discrepancy again hinges on the growth rate of execution time. By keeping the problem size at each node as small as possible far less resources are required to obtain a solution.

4.2.3 Computer Power vs. Problem Size

Another interesting experiment is to determine how much computer power is necessary to maintain the system at some percentage of optimal (in this example, approximately 75%). This is illustrated in Figures 4-12 and 4-13. Two points can be seen from these graphs. First, note again that the overall computer power needed for the hierarchical architecture is much less than the computer power needed for the centralized architecture. Second, it is also necessary to increase the computer power much more in order to keep the system at a constant level of performance.

4.2.4 Performance vs. Management Complexity

The final parametric analysis (Figure 4-14) illustrates the disadvantages of the hierarchical scheme. The system performance drops as management complexity increases. In addition, system peformance is sensitive to this particular variable. The estimation of this variable is difficult, and more research is needed before defining a system based on these results. The important result is that all of the advantages of the hierarchical system can be quickly canceled out by poor planning management algorithms.

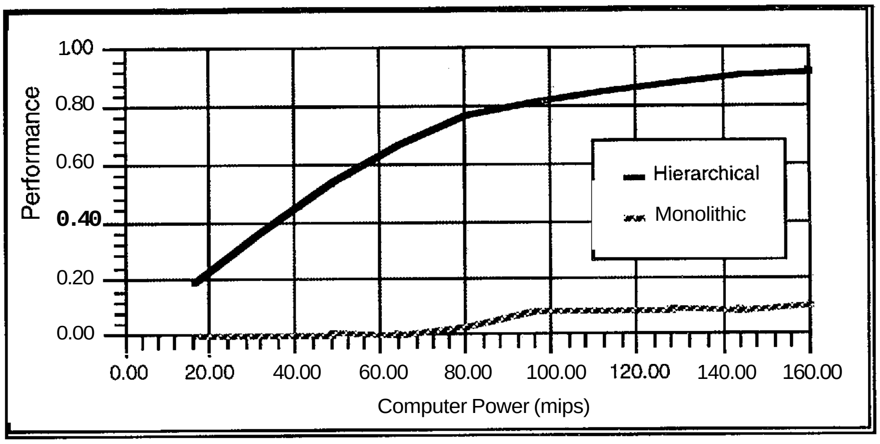

Figure 4-11. Hierarchical and monolithic planning performance as a function of computer power.

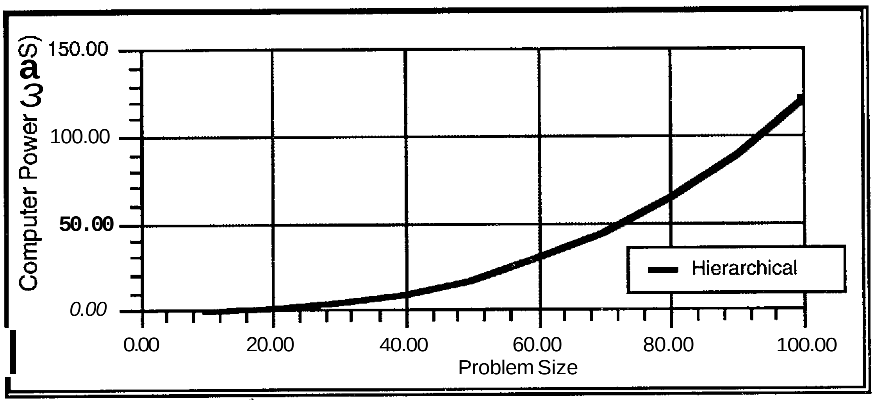

Figure 4-12. Hierarchical computer power needed to keep plan performance at a constant value as a function of problem size.

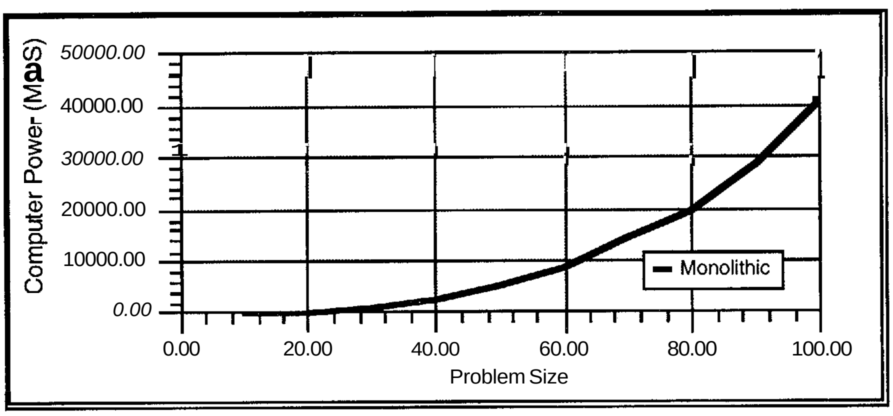

Figure 4-13. Monolithic computer power needed to keep plan performance at a constant value, as a function of problem size.

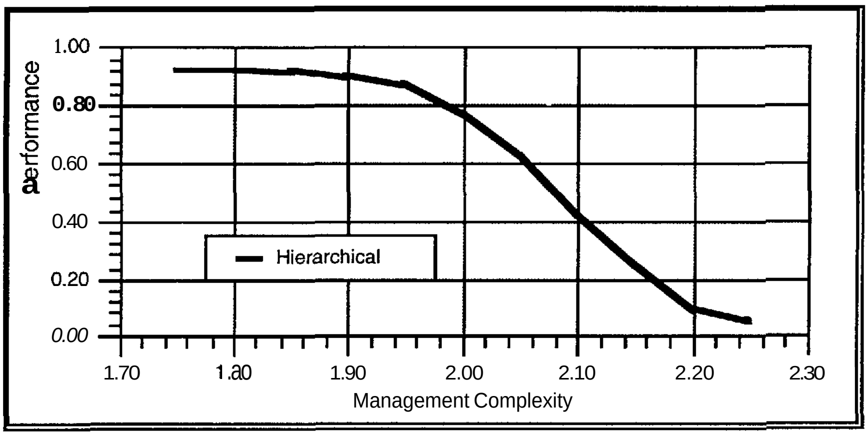

Figure 4-14. Hierarchical performance as a function of management complexity.

4.2.5 Summary

The methodology described in this paper helps to illustrate issues in implementation of the computational resources, both hardware and software, for a Mission Planning system.

The parametric studies presented here are just a few of the many possible comparisons that can be made between different planning system architectures. These types of studies would be most useful when there are specific details known for each architecture. Thus, such parameters as computer power and algorithm complexity can be fixed, and other issues such as management overhead and system architecture can be explored in more detail. In this way, an extensive analysis can be developed comparing architectures, including design specifications that would make the analysis more useful.

5. REFERENCES

[1] Kolitz, S. and Beaton, R., "Overall System Concepts in Mission Planning", AGARD Lecture Series 192, 1993.

[2] Cheeseman, Peter, "Planning and Scheduling in AI", Machine Intelligence and Autonomy for Aerospace Systems, Heer, E. and Lum, H. Editors. *Volume 115*, Progress in Astronautics and Aeronautics, American Institute of Aeronautics and Astronautics, Inc. Washington, DC, 1988.

[3] Burch, E.E. and Oliff, M.D., "Linking Level Requirements in Production Planning and Scheduling" in Production & Inventory Management v 28 n 2 Second Quarter 1987

[4] Sikora, S.E., "Implementation Issues in Hierarchical Planning and Scheduling Problems", CSDL-T-1100, Draper Laboratory, 1991

[5] Hopfield, J. J., and Tank, D. W., "Neural Computation of Decisions in Optimization Problems", Biological Cybernetics, *Vol.* 52, No. 3, pp. 141 - 152, 1985.

[6] S. Kirkpatrick, C. C. Gelatt, and M. P. Vecchi, "Optimization by Simulated Annealing", *Science Magazine, V 220,* May 13, 1983.

[7] Cormen, Thomas H, Leiserson, C.E., Rivest, R.L., "Introduction to Algorithms", The MIT Press. Cambridge, MA, 1990

[8] Kan, A.H.G. Rinnooy, "Machine Scheduling Problems (Classification, complexity and computations)" Nartinus Nifhoff, The Hague, 1976

[9] Karp, R.M, "Reducibility among Combinatorial Problems", in Complexity of Computer Computations, Miller, R.E. and Thatcher, J.W. (eds.) New York, Plenum Press. 1972

10] Bitran, G.R. and Tirupati., D., "Hierarchical Production Planning", MIT Sloan School Working Paper #3017-89-MS, Massachusetts Institute of Technology, Cambridge MA, May 1989

11] Banks, J. and Carson, J.S., "Discrete Event System Simulation", Prentice-Hall, New Jersey, 1984

MISSION PLANNING & MISSION REHEARSAL SYSTEMS - DISPLAYS AND OTHER INTERACTIVE TECHNIQUES.

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1. INTRODUCTION.

Recent years have witnessed a very rapid growth in the power of computer-based systems of all types, based on faster devices, better interfaces and the use of parallel processing. Mission planning systems have shared in this evolution and there is every reason to believe that, for the medium term at least, this increase in power will continue. The effective use of this power by the user implies that a proper collaboration is established between the user (man) and the system (machine) which can utilise to the maximum the particular capabilities of each. This requires that the greatest attention is given to the design of the interface between machine and user since the interface can significantly constrain the overall performance of the man-machine system.

This lecture describes the man-machine interface technologies which are currently available to the developer of mission planning systems, and provides descriptions of some of the advances in these technologies which are expected to become available in the short to medium term.

2. TYPES OF INTERFACE.

The following are the three principal types of information channel which are available for use as interfaces in mission planning systems:-

Visual, using the eye as a sensor for displays of machine-generated information.

Tactile, principally as an output from man through his hands, though touch feedback from machine to man can also be significant.

Speech, principally from machine to man, although the recognition of speech by machine has promise of becoming a useful technique for the transfer of information from man to machine.

The use of the eye for sending information from man to machine has had only limited use; in this case to transmit information about the eye's direction of view which is used to control the positioning of high resolution visual displays. Other types of interface, using senses such as smell, will not be discussed as they do not play any significant part in mission planning.

Each of the three principal types of interface listed above has its own set of characteristics which determine the part which it can optimally play in the overall interface design. Of the three, the visual input to the eye has the capability to transfer information at a significantly faster rate than either of the others, and is peculiarly well adapted to the mission planning and mission rehearsal problems, both of which are characterised by dynamic spatial relationships. For this reason, the display of visual information is described in significantly more detail than are the other two types of interface.

3. INTERFACE APPLICATIONS.

Man-machine interfaces are an integral **part** of all mission planning systems, and because of the different features and constraints which characterise different types of system, their interfaces are also different in many respects. It is impossible to describe all the many varieties of mission planning systems, and hence three particular types of system have been chosen which have different requirements and different constraints which determine the design of the interfaces. These are:-

Ground-based Mission Planning Systems

Airborne Mission Planning/Replanning Systems

Ground-based Mission Rehearsal Systems.

The type of airborne planning system which will be described is one which forms part of the avionics suite of the tactical aircraft performing the operational mission; for multi-crew aircraft such as AWACS, performing a command and control mission remote from the tactical aircraft, the interfaces are not dissimilar to those used in ground-based systems.

3.1 Ground-based Mission Planning Systems.

Presented at an AGARD Lecture Series on 'New Advances in Mission Planning and Rehearsal Systems: October 1993.

Systems to be used on the ground, or used in aircraft carriers, for pre-planning missions have a generally favourable environment in which to operate. Lighting conditions can be well controlled, there should be no significant vibrations, and the user will not be encumbered with heavy clothing or gloves. Additionally, a reasonable amount of space can usually be allocated to the system and operator. The Human Factors engineers responsible for the interface are therefore able to provide solutions which are constrained only by the design of the interface itself and not by the environmental surroundings.

3.1.1 Displays

Information to be presented to the user consists primarily of numerical data presented in tabular form, and terrain and feature data presented on maps. It is the latter which determine the **standards** required for the display, these standards being generally similar to those used in other graphics workstation applications such as computer-aided design. Further detailed description is given in section 5 below.

3.1.2 Tactile Inputs

The normal mechanisms for inputting data from the operator to the machine are standard QWERTY keyboards and mouse or roller-ball devices. As these are so widely used, no further description will be given. It may be questioned, however, whether it is really sensible to expect aircrew to plan missions on the ground using one type of interface mechanism and subsequently to replan them in their cockpits using totally different types of interface.

3.1.3 Speech

The benign environment of ground-based mission planning systems should be ideal for the use of speech in the man-machine interface and, as described in Ref.1, experiments have shown that the use of speech in certain types of problem-solving has considerable advantage over other means of communication. Speech communication from man to machine can be achieved by the use of speech synthesisers, and as these have now reached an advanced state of development, there is no doubt that simple messages, particularly those involving numerics, could very easily be sent and received. Speech communication from man to machine requires the use of computer-based speech recognisers; these are now coming onto the commercial market with acceptable recognition performance although the vocabulary is rather small and initial setting-up to match individual speakers is usually necessary.

The author is not aware of any published reports on the use of speech in mission planning systems, but as the technology continues to improve it seems unlikely that attempts will not be made to add speech to the other interface methods being used.

3.2 Airborne Mission Planning/Replanning Systems.

As compared with the on-ground situation, in the tight confines of the cockpit of a tactical military aircraft there is no room for equipment specifically devoted to mission planning. The man-machine interface for the mission planning function must therefore be the same as that **used for** other purposes during the mission. In addition, the environment is extremely severe, in terms of space, vibration levels, lighting levels and noise levels, and the aircrew are wearing clumsy clothing and gloves. **A** further disadvantage is the fact that, if it is the pilot who is to attempt mission replanning, his attention must be primarily given to other tasks, including that of safely flying the aircraft!

Faced with these difficulties, it is clear that the in-flight mission planning or replanning task must be much simplified as compared with that performed on the ground. The principal interfaces, which are used for other purposes, and may be optimised for those purposes, are as described below.

3.2.1 Displays.

The principal displays available to the pilot and to other aircrew are the head-up display and multi-function head-down displays. For mission planning, the head-up display is of very limited use as it is normally monochrome and the display format is confused by being mapped against the real-world background. The multi-function head down is therefore the only display of any real usefulness for planning purposes. Again, the requirements for the display of maps are the most demanding. Colour Cathode-Ray Tube (CRT) Displays are now available which can give reasonable performance in the high-brightness environment of a cockpit, and these are now being challenged by Liquid Crystal Displays (LCD's) of comprable performance These are further described in Section 6.

3.2.2 Tactile Inputs.

Because of the physical constraints in the cockpit, high vibration levels and the use of gloves by the pilot, it **is** not practical to use QWERTY keyboards. Instead, very much simplified keyboards are used; these are usually arranged so that inputs of numerical data are made by one set of keys, while other functions such as changing of display formats are inputted by dedicated keys arranged around the display surfaces. Analogue inputs can be by miniature equivalents of roller-balls; these may be mounted on the control stick if the pilot is expected to use them during manoeuvring flight.

Overall, the pilot's ability to make manual inputs to an airborne planning operation is severely constrained by the physical limitations of his interface. For a rear-seat operator, the situation is slightly less difficult but is still far worse than in a ground-based system.

3.2.3 Speech.

The sound environment in a cockpit is generally severe, although modern helmets with their attached headphones and microphones do provide some amelioration. The audio channel can be congested with high priority traffic. Thus it seems unlikely that airborne mission planning will use this channel to any significant extent even though the technologies of voice synthesis and voice recognition have made significant advances in recent years.

3.3 Mission Rehearsal Systems.

The term "Mission Rehearsal System" encompasses a wide range of equipment levels, from a simple facility embedded in a conventional ground-base mission planning system to a full mission simulator which may be used for both training and rehearsal. Proper discussion of the interfaces is only possible by concentrating on one particular level, and the level chosen is the most severe, that of full mission simulation. In this case, there are usually no constraints on the physical size or on the environment in which the simulator is to be used. except if the simulator is intended to be mobile.

In the case of the simulator, the personnel involved'in the rehearsal operation can be several: typically they will include the aircrew who will fly the simulated mission together with other personnel engaged in the planning function and in the assessment of how well the crew are able to execute the mission as it is simulated. The latter will be using a highly complex computer system but the interfaces for this will be conventional and of no particular interest. The critical interfaces will be those of the aircrew flying the mission.

The aircrew interfaces will be as near to those of the real aircraft as is economically possible and, as is well known, a virtually identical simulation is achievable for the sound channels and the tactile cockpit controls. The real problem in creating a realistic mission simulator is to provide adequate visual simulation, both of the real world as seen through the windscreen/transparency and also of the displays of TV and FLIR sensor information. This problem is studied in depth in Section 7.

4. THE DESIGN OF DISPLAY SYSTEMS

A display system for a mission planning system can be considered, in its simplest form, as consisting of the three elements shown in Fig.1. There must first be a store of information, a data base, which contains all of the information which may need to be presented to the operator. Then there must be a processor which, upon command from the operator, selects the appropriate data from the data base and re-formats it so that it is in a form which can be input to the display. The third element is the display itself which transforms the output from the processor into a pattern on a display screen so that it can be seen and understood by the operator using his eyes as sensors.

The information displayed in mission planning displays is usually of two types, alpha-numeric (i.e. letters and numbers) and graphic (i.e. pictorial). In some formats, such as maps, a combination of these is shown. Because the presentation of alpha-numeric information is relatively easy compared with that of graphical and combined information, only these latter will be considered. The processor of Fig.1 is then of a special type often known as a graphics processor or image generator.

The three elements in Fig.1 form a chain along which information is passed, the chain continuing to include the operator's eyes as its final link (the further extension to the brain is not discussed in this section). To allow this chain to perform effectively it is important that the characteristics of each of the elements shall be reasonably well matched. Thus, for example, there would be no value in displaying information at a higher spatial resolution than can be resolved by the eye since much of that information would necessarily be lost. Equally, if the dispayed information is of very low resolution, the potential of the eye as a receptor of information is not being used to full advantage, and in addition some discomfort may be caused to the viewer.

The designer of the chain can specify the characteristics of each of the three elements, within limits set by the available technology, to suit the particular requirements of the mission planning system. The characteristics of the operator's eyes are, however, already fixed and hence must dominate the design of the chain and ultimately affect each of the elements. For this reason these features are described briefly in the following section.

4.1 The Characteristics of the Human Eye.

The eye's performance as a receptor of the visual scene is extremely complex and only an outline description is given here: more detail is given in the many texts (e.g Ref.2) on the subject. In the context of the design of display systems the following are the most important characteristics:-

- Resolution / Acuity
- Sensitivity to Brightness
- Sensitivity to Colour
- Sensitivity to Contrast
- Sensitivity to Flicker
- Field - of - View
- Stereopsis

Many of these characteristics are interrelated. For example the sensitivities to colour, to contrast and to flicker are all strongly affected by the level of brightness of the perceived scene.

The ability of the eye to resolve detail is of particular importance. Fig.2 is typical of the performance which has been measured using normal healthy subjects: it shows the eye's resolution as a function of the overall illumination of the visual scene. For objects close to the visual axis of the eye the resolution at brightness levels of 1 cd m^{-2} is about 0.25 mr (about 1 arc-minute); this corresponds to the condition of the image being focussed upon an area of the retina wholly populated by cones, The resolution falls off steadily from this central condition until, at 30° off-axis where the retina is populated entirely by rods, the resolution is only about 10 mr (about 30 arc-minutes). This peripheral vision is achieved at lower brightness levels, is insensitive to colour. and is more sensitive to flicker than the central region.

Most displays appropriate for mission planning will be designed to match the flat **part** of the central-region curve, ***so*** that a display resolution of better than 1 mr should be specified. This resolution is normally required over the whole of the display because, although the eye's resolution falls off progressively away from the central region of about 100 mr diameter, eye movement and head movement are usually used by the observer to image any required part of the display onto the centre of the retina.

Flicker sensitivity is important because, with electronic displays, the pattems written on the display surface must **be** periodically refreshed: if the refresh rate is sufficiently frequent the eye sees a steady display, whereas if it is relatively infrequent the display will appear to flicker. A refresh rate of 60 frames per second is usually specified and under most visual conditions this will be sufficient to prevent any perception of flicker.

Field-of-View of the eye itself may not be particularly important because of the rapid movements of the eyes within the head, and the rather slower movements of the head itself. Thus in designing most displays it is assumed that these movements are taking place even though the display surface may not subtend a very large angle at the eyes, since the eyes' optical axes are usually directed to areas of interest where the maximum resolving power is needed. For mission rehearsal, where the visual scene may need to simulate that seen from the actual aircraft, it can be important to use displays with very large angular subtends in order to create images which are seen peripherally.

Stereopsis is the ability to judge three-dimensional scenes using the different images seen by the two eyes of the observer. Some work (e.g.Ref.3) has been done to assess the use in simulators of displays which create a stereoscopic effect by presenting different images to the two eyes, but their value has not been established and few such displays have been used in operational flight simulators. Stereopsis will not be considered further.

5. MAP DISPLAYS FOR GROUND-BASED MISSION PLANNING.

The presentation of a map on an electronic display surface is normally done in a pipeline process which comprises the three main elements shown in Fig.1, database, graphics generator and display. The problem is greatly simplifed, **as** compared with the generation of perspective displays which will be discussed later, by the fact that maps of the terrain and **of** terrain features are invariably drawn **as** though the terrain was viewed from a point vertically above the centre of the terrain and at an infinite distance from the terrain. If the data base is stored in an orthogonal coordinate system also based on horizontal and vertical axes, then the geometric transformations required from the graphics generator are very simple and comprise only the following:-

Scaling
Slewing in two horizontal directions
Rotation about a vertical axis.

The graphics generator may also be required to create symbology which may move fairly rapidly around the screen, but even allowing for this requirement, the task can **be** fairly easily met by many microprocessor-based computers which are widely available in workstations. In addition, for map displays used in aircraft, the power of modem airborne computers is such the they can readily produce any type of map and graphics format required.

The principal difficulties in generating electronic map displays therefore arise within the other two parts of the pipeline, i.e. in the creation of appropriate databases and in the design of the displays themselves. These two areas are described in detail in the following sections.

5.1 Databases for Ground-based Mission Planning Systems.

Digital Databases are now becoming available in many countries, and are being produced by **both** civil and military authorities as well as by industry. Although much of the data is available in formats which do not correspond to any internationally-agreed **standards,** such data can generally be readily transformed off-line into whichever formats are being used for specific applications. Prominant among the digital data available are the **US** DTED (Digital Terrain Elevation Data) and DFAD (Digital Feature Analysis Data), which can be provided in a range of different scales and accuracies, the most detailed corresponding to that of a 1:50,000 scale map. This is almost invariably sufficiently accurate for mission planning unless pin-point accuracy relative to individual buildings is required.

Mission planning requires that this data contains all the features which can affect the safety and success of the mission, and it is in this area that the most problems can arise. In a peacetime scenario it is unlikely that the data will be reliably updated in terms of power lines or other tall man-made features. In a wartime scenario, updating may be needed at frequent intervals to incorporate the positions of friendly and enemy assets; such information is generally provided from intelligence sources and is unlikely to be in a form compatible with the digital **dala** base information, Thus to input intelligence information into a mission planning system generally requires significant manual operations.

5.2 Display Devices for Ground-based Map Displays.

Electronic displays of map information which are to be used on the ground are almost invariably in a reasonable environment in which a fairly large display screen can be used and the ambient light level can **be** well controlled. This is also true of displays to be used in airborne command-posts such as the AWACS type of aircraft.

If maps are to be created which have a quality even remotely approaching that of conventional paper maps, the only technology which is currently available is the Cathode Ray Tube (CRT). The principal commercial application for high quality cathode ray tubes is that of engineering design, using Computer-Aided-Design (CAD) techniques, and this application has provided the commercial incentive to advance the state-of-the-art in high quality CRT's in the past decade. Although alternative technologies, such as liquid crystals, have also made notable improvements, it seems unlikely that they can seriously challenge CRT's in the forseeable future. A typical high-quality CRT intended for CAD use might have the following principal characteristics:-

Full colour (by using a screen with 3-colour triads)

Size 400mm horizontal, 300mm Vertical

Raster pattern (approx) 1200 pixels per line, 1000 lines.

The total number of individual pixels (picture elements) which can be displayed is about one million, and if refreshed at 60 Hz to avoid apparent flicker, a video clock speed of about 100 MHz is necessary, which is currently possible with suitable drive circuitry. These circuits are now available as graphics cards which themselves contain significant computing power and memory to offload much routine computation from the main graphics computer. If the map scale is changed, or the map needs to be rapidly slewed, the response may be a little slow, but this is not normally seen as a significant problem in use.

A CRT of this size, when viewed at a typical workstation distance of 400 mm, will generate pixels which each subtend about 0.75 mr at the user's eyes; this is rather larger than the resolution of the eye, and hence the raster structure of the map display will be seen. By comparison, a map of 1:50,000 scale might typically have a size of 1.5m horizontal by 1.5m vertical, with a resolution better than 0.1mm, giving a possible total of over 10^8 pixels. Such a map is noticeably sharper than an electronic map, as well as being bigger, but the advantanges of an electronic map, such as ability to change scale, slew, rotate and select types of feature, are such that the map displays will inevitably be electronic in all current and future systems.

It is likely that future CRT's will be able to provide further increases in resolution and size. Displays of 2500 pixels and 2000 lines in sizes up to 500mm by 500mm are already in production, although they are not yet available to military standards. As high definition television becomes established, a sufficient market may be created to force prices of high quality displays (including the associated electronics) to fall significantly. This market may also provide the stimulus for the development of alternatives to the CRT, particularly for large screens designed for simultaneous viewing by numbers of persons; such screens might be useful if the mission planning system was used also for briefing purposes.

6. MAP DISPLAYS FOR AIRBORNE MISSION PLANNING SYSTEMS.

6.1 Databases for Airborne Map Displays.

For airborne map displays to be used for mission planning purposes, the required database information is generally no more detailed than for the ground-based systems discussed above. However, the problem of updating is significantly aggravated since the aircrew (unless the aircraft is a command-and-control centre such as AWACS) is unlikely to have sufficient time for updating manually using intelligence information. Thus it seems likely that, except for very simple updates, the database must remain unchanged throughout the mission

6.2 Display Devices for Airborne Map Displays.

The problems associated with displaying maps in the cockpit of a military aircraft are very considerable. Firstly, the size and position available for the display are far from optimum, the screen size being typically about 125mm by 125mm and the screen position being below and/or to the side of the central head-up display which inevitably takes the prime position in the pilot's field-of-view. Secondly, the cockpit transparency ensures that a high level of ambient light will often be present, and that sunlight can often shine directly onto the front surface of the screen. Thirdly, there may be significant vibration in the cockpit which will affect the resolution performance of the pilot's eyes.

Although some current map displays use optical projection systems to reduce the effects of ambient light and of vibration, modem practice is to provide very bright displays which are viewed directly. Such displays usually have much lower pixel performance than workstation displays; typically a raster pattem of 250 lines each of 250 pixels is used, It may also be noted that the colour performance is seriously affected by the strong ambient light so that colour discrimination by the pilot is degraded.

Much effort has recently been devoted to the improvement of colour displays for cockpit use and new techniques are beginning to come into use, particularly liquid crystal displays, which in some respects give performance improvement over CRT's. Particular areas of improvement are size and brightness, the latter providing improved colour rendition in high ambient illumination. But it is certain that the overall performance will always be considerably below that of ground-based displays.

At the other end of the ambience scale - nighttime operations - there is a different problem which arises if the pilot is wearing night vision goggles. These will significantly compromise his ability to perceive detail on a map display because they are monochrome and have a resolution capability far below that of the human eye.

Perhaps of more importance than display performance is the fact that a pilot must necessarily divide his time between several tasks and hence will not be able to concentrate his attention on an airborne map display for long periods at a time. Taken together with the performance limitations already noted, the result is that display formats have to be designed to be much more simplistic with a lower information content than those intended for ground use, and for this reason the design of airborne display formats has received much attention over many years. It is clear that the use of mission planning systems in the cockpits of future tactical aircraft could be significantly limited by the simple formats that will have to be provided on their map displays.

7. **PERSPECTIVE DISPLAYS** FOR **GROUND-BASED** MISSION REHEARSAL.

The generation and display of perspective scenes is a much more complex and difficult problem than that of maps; the four main reasons for this are:-

(i) The geometric transformations which relate the displayed view to the terrain coordinate set can have six independant degrees of freedom as compared with only three for a map which is constrained to the horizontal plane.

(ii) If the display is to be used for real-time mission rehearsal, it is probable that the angular transformations will correspond to the orientation of the aircraft relative to the ground plane, and hence the maximum angular rates at which these transformations need to be varied must match the very high speeds of angular rotation which can be achieved by military combat aircraft. This problem becomes significantly more severe with the advent of helmet-mounted and eye-slaved displays.

(iii) The detail in the scene may be required to be much greater than in a map, particularly if the display is to be used for mission rehearsal.

(iv) The field-of-view of the display, as seen from the pilot's eye position, may be much greater than for a map display.

For these reasons no system has yet been constructed which generates a display which fully matches the visual scene as seen by a pilot flying a fairly low-level mission in a military aircraft. Nevertheless, the state-of-the-art has developed steadily during the past decade, so that images can now be generated in training simulators which are sufficiently close to the real-world scene to allow training to be carried out effectively. It should be emphasised, however, that there appears to be no rigorous experimental or theoretical basis which establishes the degree of visual fidelity necessary for different specific training tasks. Thus the visual characteristics for training simulators are usually based on previous experience of how well a similar task could be performed with earlier equipment, and also on the cost of the latest visual equipment available. As costs of computers have fallen, there has been a tendancy for improved visual performance to be specified, even though the need for this has not been established in any exact way.

For future mission rehearsal systems there is effectively no previous experience on which to base decisions on the requirements for display characteristics, and it seems highly desirable that experimental research be directed at establishing relationships linking display performance and rehearsal effeciveness. However, it seems reasonable to assume that for those missions in which the pilot is relying heavily on interpretation of the detailed visual scene (e.g. in an attack upon a ground target which is identified visually) the visual scene should be as close to reality as possible. It is clear that there are potential dangers in rehearsing a mission with incorrect or inadequate visual clues, especially in parts of the mission such as target acquisition when such clues are likely to be at the limits of the pilot's eye resolution. It may also be remarked here that many simulator displays operate at such low light levels that the resolution of the pilot's eyes is significantly worse than in a high brightness real-world situation. Hence detection/identification ranges in simulation may be quite different from reality, with corresponding differencies in performance and workload.

In the discussion that follows, a low-flying mission will be analysed and the demands of creating appropriately detailed visual scenes will be examined. It will be shown that the problems inherent in generating displays which fully represent the pilot's view of the real world are such that these displays are, for the present, impossible to manufacture. It is not yet clear whether or not mission rehearsal systems using displays of lower standard will provide effective rehearsal performance.

7.1 Practical Specifications.

It has been noted above that no real basis exists for deciding the required performance for a visual display system for a mission rehearsal simulator, and also that for various reasons a fully representative scene is beyond the capabilities of any system thus far developed. Hence some compromise must be reached. Three of the key questions which need to be addressed in making this compromise are shown in the decision tree in Fig.3, and the answers have to be assessed in terms of their effects upon the components in the system chain as shown in Fig.1. The questions are:-

(i) Is real-time representation required? The answer to this question has a strong influence upon the speed at which the computations in the graphics generator are carried out, and if slow-speed or "snap-shot" reproduction of the visual scene is acceptable the cost and complexity of the image generator are significantly reduced.

(ii) Is hands-on capability required in the rehearsal simulation? The significance of this question is that if the pilot is to have the freedom to steer the aircraft through the simulated visual scene, the display must be capable of showing the scene from any position and any attitude. This precludes the use of "pre-computed scenes which can be stored and retreaved at the required real-time rate. This again has a strong influence upon the complexity of the image generator.

(iii) Is true scene detail required? As there is no virtue in displaying a visual scene with more detail than the pilot's eyes can resolve, this question effectively asks whether scene detail matching his resolution is required. The answer has implications for each of the elements of the system chain.

There are many system options which can be chosen in response to these questions; these will depend strongly on the type of mission and also on the availability of data to construct the data base which is holding all the information necessary to generate the visual scene.

The information content in the earth's visual scene is much greater than in specific man-made targets such as aircraft. Thus the difficult missions to simulate are those in which the pilot has a good view of terrain detail from a low level.

The difficulties of providing adequate visual scenes in simulating low-level operation are most serious in the case of helicopters. There are several reasons for this, of which the principal one is that operation can be very close to the ground a height of 20 metres is not unusual in some operations. Also, the crew is likely to be looking down at a greater depression angle than in the fixed wing case, perhaps down at 30° to the horizontal.

Using the expressions quoted in Ref.4, and with an eye resolution of ***0.5*** mr, the corresponding values for the resolution of ground detail as perceived by the eye are:-

Vertical resolution at the ground = 0.025m.

Horizontal resolution at the ground = 0.04m.

These are such small values as to make it almost impossible ever to create moving visual scenes of this magnitude of detail. Perhaps , in the future, it might be possible for very small individual features such as buildings, but the creation of a data base covering any reasonable area of terrain at this level of detail appears to be unattainable.

Another major difficulty with the simulation of helicopter operation is that because the vehicle can have quite small groundspeed, the crew will look around through a relatively large arc of vision, much larger than in fixed-wing operation. Some helicopters have bubble canopies which allow a visual field of over half the 4π steradians solid angle visible by a totally unobstructed observer. A display which could provide sufficient pixels to give resolution of 0.5 mr over a field of view of 2π steradians would have to contain some 2.5×10^7 pixels. This is much greater than any currently available display.

For these reasons, it has not so far been possible to design visual simulations of a quality really adequate for the training of low-level helicopter operations, and it does not seem likely that suitable equipment will become available in the forseeable future. Practical experiments using currently available technology are described in depth in Refs.5 & 6. Realistic simulation for mission rehearsal is equally difficult, with the added problem that data bases may need to be created in a much shorter timescale.

7.2 Databases for Perspective Displays.

The creation and updating of databases for perspective displays is potentially one of the most difficult aspects of advanced mission planning and rehearsal systems, particularly if the display to be generated is to give a picture which is visually close to that of the real world. As discussed in previous sections, the worst-case is for tactical aircraft and helicopters operating close to the ground, because the required scene detail is much greater than for map displays, and this requirement forms the basis for the discussion which follows.

High resolution databases may be built up from the following:-

(i) Standard databases such as Digital Feature Analysis Data (DFAD) and Digital Terrain Elevation Data (DTED).

(ii) Reconnaissance Data from aircraft and satellites, usually in the form of images.

(iii) Libraries of standard features and textures which approximate to the features and textures in the actual scene being recreated.

(iv) Intelligence data.

The extent to which standard features and textures can be used instead of specifics depends very largely upon the height of the operating aircraft and the use to which recognition of the scene is being put; in target areas it may be found inappropriate to use them because they will be insufficiently representative of the real world.

The building of a complete database from these four types of data can be a difficult process. Amongst the reasons for this are:-

(i) The scale, resolution and coordinate bases of the standard digital data may not be the same.

(ii) Image data may have ill-defined coordinates and totally random directions of viewing.

(iii) Image data may have been obtained in different lighting conditions and have different cosmetic quality.

(iv) The synthesis of feature geometry from image data requires the combination of more than one image to obtain perspective information, or else the interpretation of shadow dimensions.

(v) Features and terrain may not combine together in a way which is cosmetically satisfactory.

(vi) Intelligence data may be generated in a variety of forms which are likely to be incompatible with database standards.

(vii) Information provided from different sources may be inconsistent. Inconsistencies between the completed mission rehearsal perspective database and the simpler map database used for other mission planning functions could cause major problems during the overall planning process.

For these reasons there is inevitably a large amount of skilled manpower involved in the creation of a database suitable for the simulation of **a** low-level scene of a complex area of the ground with man-made features such **as** buildings. Because of the penalties of including more scene detail than necessary, they **are** usually optimised for specific types of mission and are not generally usable at significantly different heights. Refs.7, **8** & **9** provide excellent accounts of the techniques used **to** build data bases.

The need for human judgement in the building of these databases implies that this is done ahead of the on-line creation of the displayed scene by the scene genarator. However, with the development of mission rehearsal systems and the need to reduce database preparation times as much as possible, efforts are being made to carry out part or all of the building during run-time. So far, this has only been fully done with workstation-based systems in which DTED and DFAD information is directly used in the generation of scenes, but without the complexities of using additional data such as photographic images. However in the ESIG-4000 computer system being developed for a **U.S.** Air Force mission rehearsal system (Ref.10), which uses image data as well, the features and the terrain are built up **as** two separate databases which are then combined in real-time: this is claimed to give advantages in savings of database preparation time for which a total of 48 hours has been specified to construct a database for a target scene which includes a number of highly detailed buildings and other features.

Databases must be constructed so that the data is stored in a format from which it can be extracted by the image generator. In many cases this implies that the format is specific to the design of the display generator and, since most manufacturers have their own individual designs of generators, the format is specific to each manufacturer. As an example of these differences, terrain data is sometimes stored in rectangular coordinates and sometimes by means of polygons. In addition, most data is stored using some degree of data-compression, and again the method used tends to be company-specific. For the users these are major disadvantages since a database constructed for one display system cannot be used for another without expensive and time-consuming re-formatting. An initiative has been taken by the U.S. Air Force with the Project 285 1 (Ref.11) which is trying to set standards for simulation databases, but the problem is proving to be extremely difficult.

All of the above discussion has assumed that the scene to be generated is a representation of the pilot's visual scene. For most missions which involve target attack it is equally important to simulate the scene which would be generated by a sensor, such as **a** FLIR, looking forward from the aircraft. Such scenes can be created from the same database **as** the visual scene but need additional parameters which characterise the IR behaviour of the terrain and the features.

7.3 Image Generation.

The function of the image generator, as shown in Fig.1, is to take data from the database and to construct an image of the visual (or sensor) scene taking account of the geometry of the aircraft relative to the terrain coordinates. The output signal is fed to the display in a format defined by the display characteristics; usually the format is a raster standard specified in terms of the number of lines, the frequency or pixel content of each line and the refresh rate.

Although each manufacturer of image generators has his own design for performing this function, and these differ in detail, most conform in general layout to that shown in Fig.4. This figure shows at the left the combination of data into an appropriately formatted database, which is not really an image generator function and is usually carried out off-line, but which has to be considered **as** part of the overall design process to ensure compatibility of formats. The on-line pipeline system which forms the image generator comprises four processors which successively perform the following transformations:-

The Perspective Processor takes the database model and, using data concerning the geometry of the aircraft relative to the terrain, computes the terrain and feature geometry in display coordinates.

The Raster Processor reformats the perspective geometry into the display raster format.

The Pixel Processor takes the raster signal and, using depth data from the Perspective Processor, deletes information on surfaces which are hidden from view by nearer surfaces. Using texture, shading and colour data from the database it calculates the pixel brightness and colour for each pixel on the display.

The Frame Buffer is a store in which all the pixel information is accumulated so that it can be read out at intervals determined by the display clock.

An estimate has Seen given in section 7.1 of the number of display pixels required **to** give a display which is really adequate for low-level flight, but this is beyond the resolution of the best displays. As will be noted in **7.4,** most raster displays have no more than 3x106 pixels which need to be refreshed at 50 or 60 Hz to avoid perceptable flicker, and thus a pixel data rate of 1.5×10^8 per second is required. In practice the data rate from even the most powerful image generators currently available, such as the GE Compuscene **5** and the E&S ESIG 4000 is less than 10^8 per second per channel so that parallel pixel processors may be necessary. Parallel operation of several perspective processors may also be required to provide adequate throughput.

The operation of four processors in pipeline necessarily implies significant time delay between **a** change of the input geometrical data and a change in the displayed image. Top-end systems have overall transport delays in the 60-70 ms range, and this is only just adequate to prevent the delay becoming perceptable to the pilot.

Although performance figures for highquality, high-cost image generators have been mentioned, it should be noted that modem workstations are now so powerful, and have so much capacity for operating in parallel, that they are beginning to make significant inroads into the training simulator market. It is reasonable to predict the this will be followed by progressive inroads into the mission rehearsal area, but the extent of this is difficult to predict as there is, as yet, no clear agreement on the display resolution requirements for rehearsal systems. The use of workstations for rehearsal purposes within a mission planning system also based on similar workstations has obvious advantages in terms of first cost, compatibility of data standards and ease of maintenance and support.

7.4 Display Devices and Optics.

The third element of the system shown in fig1.1 is the display device which transforms the signal from the image generator into a visible image. Because of the need to match the eye's characteristics the image should ideally be full-colour, high resolution, wide field-of view and collimated into the distance, but display devices to meet this requirement are necessarily very complex and very expensive. More simple displays are sometimes used which may be adequate for particular tasks in training simulators, but the lack of any real experimental evidence on the appropriate performance levels for mission rehearsal displays makes it difficult to provide guidelines on the type of display which should be chosen for future mission rehearsal systems.

A brief description of some of the display types used in training simulators is given below: mission rehearsal displays will be similar and it is likely that training and rehearsal could be carried out on the same facility.

7.4.1 Directly-Viewed Displays

The simplest type of display creates an image on a single surface which is viewed directly by the pilot. To obtain resolution close to required levels combined with a reasonable field-of-view currently implies the use of a Cathode Ray Tube, although other display types such as liquid crystal screens are starting to challenge the CRT. The sizes and standards in use are the same as those already described in 6.2 as being suitable for map displays.

The main advantages of a simple display of this type are their cost and their compatibility with existing designs of commercial workstation. The main deficiency is the very restricted field-of-view which is likely to make it unusable for some types of mission, such as helicopter operation close to the ground.

Larger CRTs with up to 2000 by 2000 pixels are now becoming available although they are not yet sufficiently rugged for some military applications, but any directly-viewed single-screen display will always be seriously deficient relative to the likely requirements for mission rehearsal.

In some training simulators the CRT is viewed through a collimating optical system which, in its simplest form, can be a simple pancake lens. Although some realism is added by image collimation, there remains the fundamental disadvantage of narrow field-of-view.

7.4.2 Multiple Displays

Several alternative arrangements have been adopted in training simulators to provide more representative fields-of-view, and these are likely to be considered also by designers of rehearsal systems. The two basic options available are:-

(i) Several CRT displays mouted side-by-side and either viewed directly or through optical collimators.

(ii) One or more projection displays which illuminate a screen, often in the form of a dome, on which the image is focussed.

The use of more than one display can be convenient in the overall system design since each display can be interfaced with a separate processor allowing the image generation to be shared between parallel processors. The main disadvantage is increased complexity and the difficulty in obtaining a complete visual scene with acceptable continuity between the separate images. The projection systems also suffer from generating brightness levels much below real-life.

Display systems of these types are used in almost all full-flight training simulators, and a dome version is the baseline choice for the USAF Special Operations Forces mission rehearsal system (Ref.10). The need for alternative systems which are better matched to the head/eye characteristics has led to the development of more radical solutions which are discussed below.

7.4.3 Heamye-Slaved Displays.

For many military aircraft, and particularly for helicopters, the wide canopy allows the aircrew to view the outside world over a very wide arc, using a combination of head and eye movement. As the head and eyes are moved, the instantaneous field-of-view occupies only a small part of the total swept field-of-view, so that the remaining part cannot be seen. It follows that a fixed simulator display which covers the total field-of-view is always providing an image of which only a part can be seen at any instant. By moving the position of the displayed image in space so that it is always centred upon the eyes' centrelines, this waste of image can be averted and considerable image display and processing can be saved.

Slaving the display image to the eyes requires knowledge of eye pointing direction, and this is not easily measured. A simpler concept, which is easier to implement, is to measure head orientation and slave the display position to it; the display must then have a field-of-view equal to that of the eyes plus the maximum angular movement of the eyes within the head. A number of research and training simulators have used this technique (Refs.12 & 13) and there are several suitable head position sensors commercially available. The display is usually of the projection type using a dome screen. *An* altemative and much simpler arrangement is to mount the display on the pilot's helmet so that it automatically follows the head movement, but helmet-mounted displays have disadvantages of limited field-of-view and resolution as well as being rather clumsy to wear.

It is likely that research into the techniques of measuring eye position will, in the near future, generate compact and accurate sensors that will enable the eyes' point of regard to be accurately determined. This will allow the so-called point-of-regard displays to be developed as practical simulator devices. In these displays advantage is taken of the eye resolution characteristics described in 4.1 and illustrated in Fig.2. The displayed image is configured to have a central high-definition area corresponding to the central high-resolution area of the eyes, together with a lower definition area for the remainder of the field-of-view. Significant saving in image processing results, but the transport delay in the processors, which is a problem with helmet-mounted displays (Ref.13), has to be reduced to prevent perceptable lags with rapid eye movements. As with head-slaved displays, point-of-regard displays will probably be mainly of the projection type with the complication that the central and outer areas must be blended together to prevent a perceptable boundary.

The main advantage of point-of-regard displays is that, by properly matching the display characteristics to those of the head and eyes, they are able to provide levels of resolution which should be adequate for the most demanding tasks. It can be expected that, as the techniques and equipments for measuring and display-rotation become further developed, these types of display will be increasingly used in training and rehearsal simulators (Ref.14).

7.4.4. Sensor Displays.

Most modem military aircraft are equipped with imaging sensors which are used to aid the aircrew in such tasks as ground clearance and navigation, target detection, acquisition and recognition. For these purposes the sensor image is displayed to the crew on displays, usually CRT's, on the instrument panel or helmet-mounted. In providing a simulation of a planned mission for rehearsal purposes it is necessary to simulate the sensor displays with appropriate fidelity, particularly if this sensor information is critical to the success of the mission.

The display and the associated processing do not present a problem since these can be based on those used in the aircraft. The other elements of Fig.1, the database and image generator, will be similar to those used in a visual simulation, but may have the following significant differences:-

(i) The resolution may be either greater or less depending upon the effective magnification and field-of-view of the sensor.

(ii) Reflection characteristics at radar wavelengths of both terrain and features, and emission characteristics in the IR, will differ from those in the visual band and will need to be included in the database model. Speckle and glint are particularly difficult to model.

ii) Atmospheric and ambient lighting effects may need to be included which are often quite different from those used in the visual model.

Training simulators have been built in which these differences have been successfully allowed for, and the techniques used should be equally applicable to mission rehearsal simulators. It should be noted, however, that the additional contents of the terrain and feature database models, such as glint information, may require more preparation time unless they can be generated by an automated process.

One problem reported in Ref.15 concerns the need to ensure that the visual and sensor displays are properly correlated in terms of spatial content and of timing; this problem is particularly difficult when the image generators and databases for the visual and sensor images are developed by different organisations.

Ref.16 discusses the database requirements for the simulation of helmet-mounted night vision goggles which have spatial and intensity characteristics which require unique database shadow and contrast features.

REFERENCES.

1. Ince,A.N. "Advances in Speech Processing". AGARD CP-521, paper 18, 1992.

2. Wolfeck,J.W. et al. "Vision in Military Aviation". WADC Tech Rep 58-399, Nov 1958.

3. Tidwell,R.P. "Stereopsis as a Visual Clue in Flight Simulation". AIAA Paper 89-3288-CP, 1989.

4. AGARD Advisory Report AR-313, "Mission Planning Systems for Tactical Aircraft", Chapter 4, 1993.

5. Simpson,M. and Wilson,I. "Can't See the Ground for the Cues". Proceedings ITEC 90, 1990, pp 7-13.

6. Bondzeit,F. and Edwards,R.E. "Image Generation for Rotary Wing Applications". Proceedings ITSC 88, 1988, pp 380-387.

7. Geer,R.W. and Dixon,D. "Mission Rehearsal: Its Impact on Data Base Technology". Proceedings ITSC 88, 1988, pp 213-220.

8. Economy,R., Ellis,J.R. and Ferguson,R.L. "The Application of Aerial Photography and Satellite Imagery to Flight Simulation". Proceedings ITSC 88, 1988, pp 280-287.

9. Wilkerson,H. and Brown,T.C. "Scene Realism: The Synergy of Data Base Technology and CIG Hardware". Proceedings ITSC 88, 1988, pp 288-294.

10. Grange,R. "Mission Rehearsal in the SOF-ATS".

in AGARD Lecture Series LS-192, 1993.

11. Oda,K. "Project 2851 Data Base Strategies for SimulatorCorrelation". AIAA Paper 90-3168-CP, 1990.

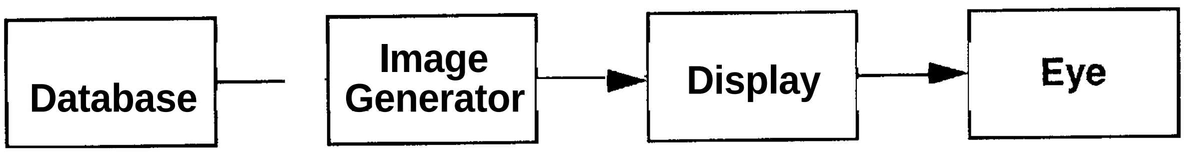
12. Haworth,L.A., Bucher,N.M. and Hennessy,R.T. "Wide Field of View Helmet Mounted Display Systems for Helicopter Simulation". **AIAA** Paper 88-4575-CP, 1988.

13. Haworth,L.A., Bucher,N. and Runnings,D. "Helmet Mounted Display Systems for Helicoter Simulation". Proceedings Human Factors Soc. Annual Meeting 1989, pp 86-90.

14. Reno,B.A. "Full Field of View Dome Display System". **AIAA** Paper 89-3316-CP, 1989.

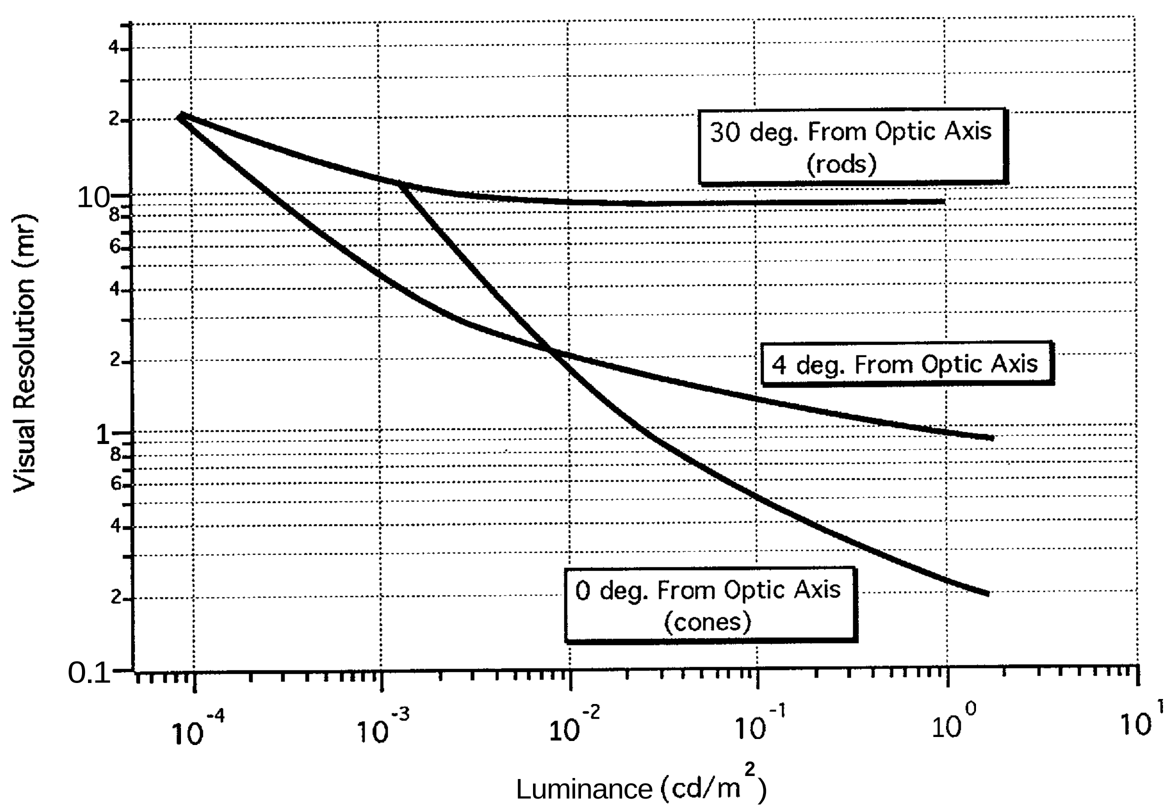
15. Widder,P.A., Phillips,D. and Hrabar,M. "Data Base Correlation Issues". Proceedings NAECON, 1989, pp ***855-862.***

16. Geer,R. "Night Vision Goggles: Terrain & Feature Shadowing for CIG Databases". AIAA Paper 89-3286-CP, 1989.



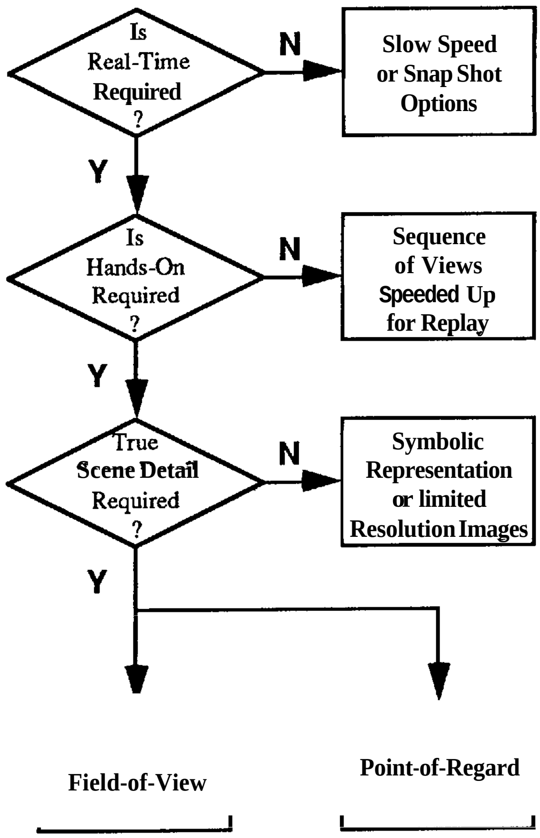
The Display/Graphics System.

Fig.1



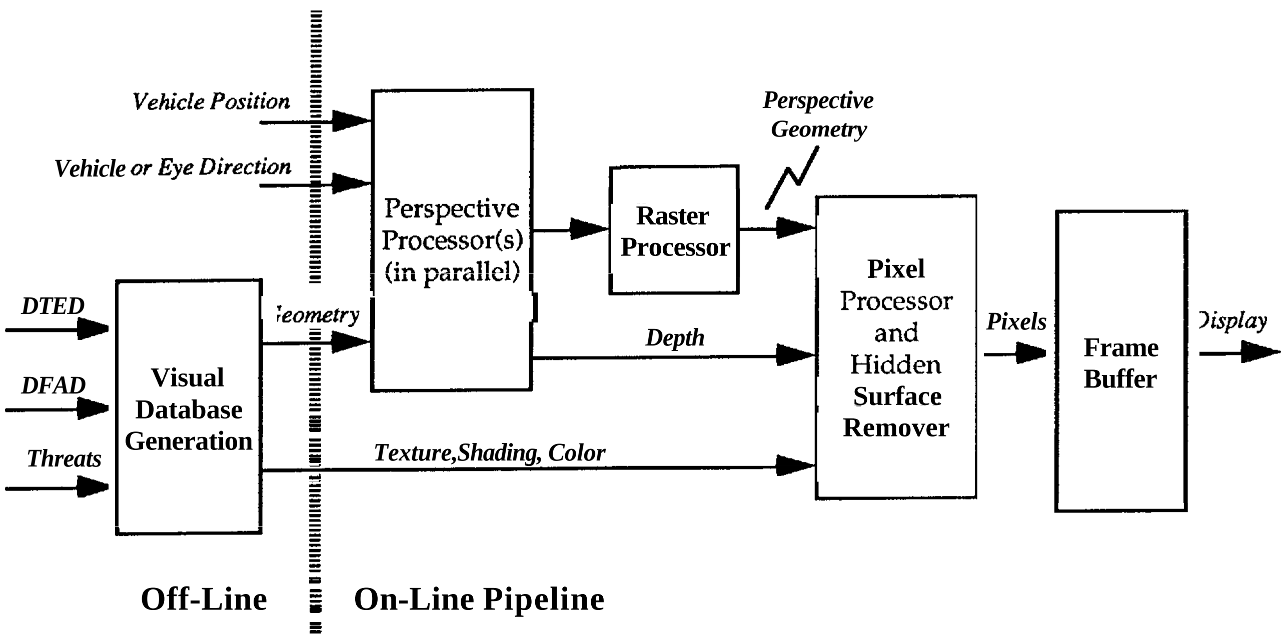
Eye Resolution.

Fig.2



Visual Display Requirements for Mission Rehearsal Simulators.

Fig.3



Typical Structure of an Image Generator.

Fig.4

GROUND BASED MISSION PLANNING SYSTEMS

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ABSTRACT

Even for complex combined missions it has been necessary for Ground Based Mission Planning to be performed as close to the individual mission as possible. With the advent of intelligent Automated Mission Planning Systems (AMPS) and reliable, secure communications, the speed of data exchange and completion of the subsequent mission planning has greatly increased. This paper outlines the mission cycle and briefly examines a range of mission tasking activity. This framework is used to describe a possible operating base tasking and planning system architecture, within which the AMPS architecture is explained. Typical AMPS databases and functions are examined before a description of the actual task definition and mission planning processes. Mission validation and rehearsal capabilities are outlined and the range of data outputs is examined. The paper concludes by briefly explaining the archiving of the resulting data.

1. INTRODUCTION

1.1 Mission Cycle

The mission cycle for sustained air operations is driven by Force Level decisions on the immediate steps to be taken to achieve the overall aim. From these initial decisions flows a pyramid of subordinate decisions on the separate elements. At each level the planning necessary to implement the decisions becomes increasingly detailed but over a narrower field. The information required to support this decision making and implementation flows down from Force Level through the subordinate levels and also in reverse to keep the Force Level informed of progress, tactical situation and asset availability.

The overall process can conveniently be divided into six phases, as follows:

- Mission Tasking
- Mission Planning
- Crew Briefing
- Mission Execution
- Mission Debriefing
- Result Reporting

1.2 Decision Aids

A number of different decision aids and information transmission systems have been developed to assist in various elements of the overall planning and reporting **task.** A better integration of these devices has been put in train by the USAF in its AN/TYQ–43 Advanced Planning System but, to date, the size of the overall task has meant that it is not possible (or even advisable) to complete detailed individual mission plans at Force Level. It therefore remains the practice to divide and deconflict mission tasking into smaller packages and to delegate the detailed planning to Operating Base Level. At this level, the final detailed planning and execution of small tasks can be allocated to individual Units but larger tasks might well require the participation of **a** combination of Units which, although operating out of the same base, are not co–located within the base. For the largest tasks, or for tasks where specialist support is planned, there is a need for the integration of mission plans for aircraft from more than one Operating Base. The resulting mission requirements form part of a series of integrated activities requiring rapid completion with careful co–ordination and deconfliction at all levels. Recent advances in mission planning and rehearsal systems have been designed to automate, integrate and speed up the mission cycle.

Presented ut an AGARD Lecture Series on 'New Advances in Mission Planning and Rehearsal Systems: October 1993.

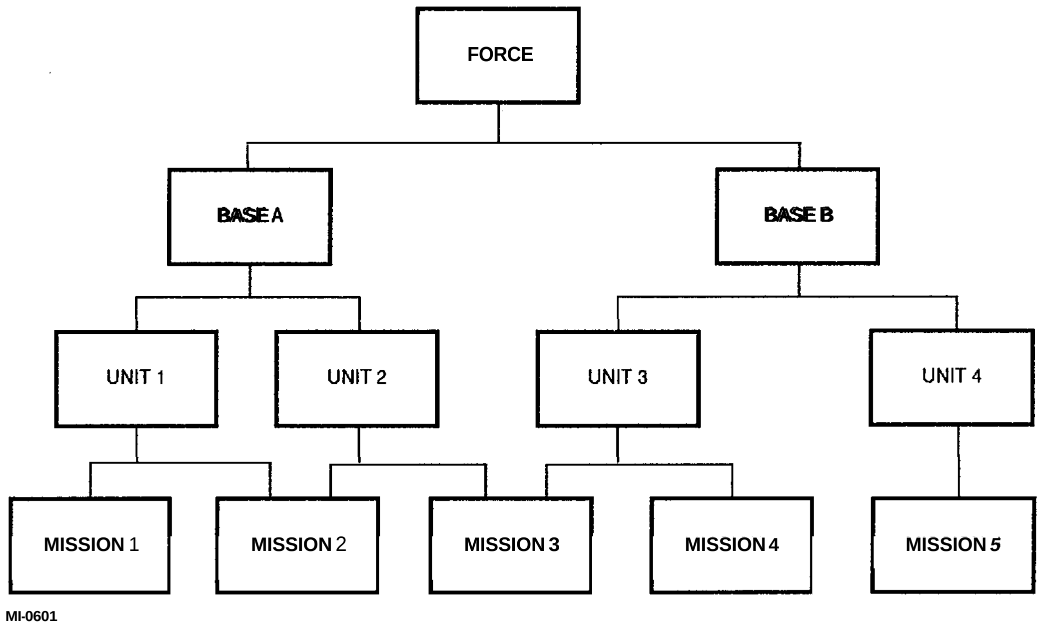

Fig. 1 Ground Based Mission Planning Scenario

1 3 Mission Tasking

A range of possible mission tasking is illustrated in the simple scenario at Figure 1. In this example, Unit 1 (operating from Base A) is tasked with two missions. One is to be completedusing its own aircraft only whilst the second requires co-operation with aircraft of Unit 2 (also operating from Base A). Unit 2 has a second mission, to be performed in conjunction with aircraft of Unit 3, operating from another Base (Base B).

Within Base B, Unit 3 has asecondmission to becompletedusing its own aircraft only and Unit **4** is also tasked with its own unit mission. In this scenario, the five missions might well have been deconflicted by area or by time at the Force Level.

Thus within theoverall framework of Force Level planning, with its top level of integration and deconfliction, ground based mission planning has been an individual Unit function with supplementary deconfliction and co-ordination assistance from its superior levels. The speed at which this planning can be completed has been very dependant upon the complexity of the individual missions and the comprehensiveness of the necessary co-ordination. The increasing automation of what has been a mainly manual process is offering a much more rapid and integrated mission planning capability.

2. AIM

The aim of this paper is to outline the Base Level setting within which which Unit Level mission planning is performed and to describe the architecture, function and operation of a typical advanced ground based Automated Mission Planning Systems (AMPS) as used at Unit Level.

3. OPERATING BASE SYSTEM ARCHITECTURE

Long term data will normally be resident within the AMPS database but communication with other agencies is required for thereceipt andupdatingofmission tasking andothermediumand short term data. Thus the Automated Mission Planning System (AMPS) forms part of an operating base system that links eventually into the overall tasking and reporting nets.

A schematic diagram of a typical operating base system architecture is shown at Figure 2. The Combat Operations Centre (COC) is responsible for the initial receipt and local allocation of the base mission tasks, together with the subsequent upward reporting of the mission results. The Air Operations element will allocate tasks at unit level, while the Intelligence element is responsible for receipt and local dissemination of the collated intelligence data, together with the subsequent upward reporting of newly observed intelligence gathered from crew debriefing. The planning element is where the detailed mission planning is completed. All the elements are connected by local area network (LAN) communications.

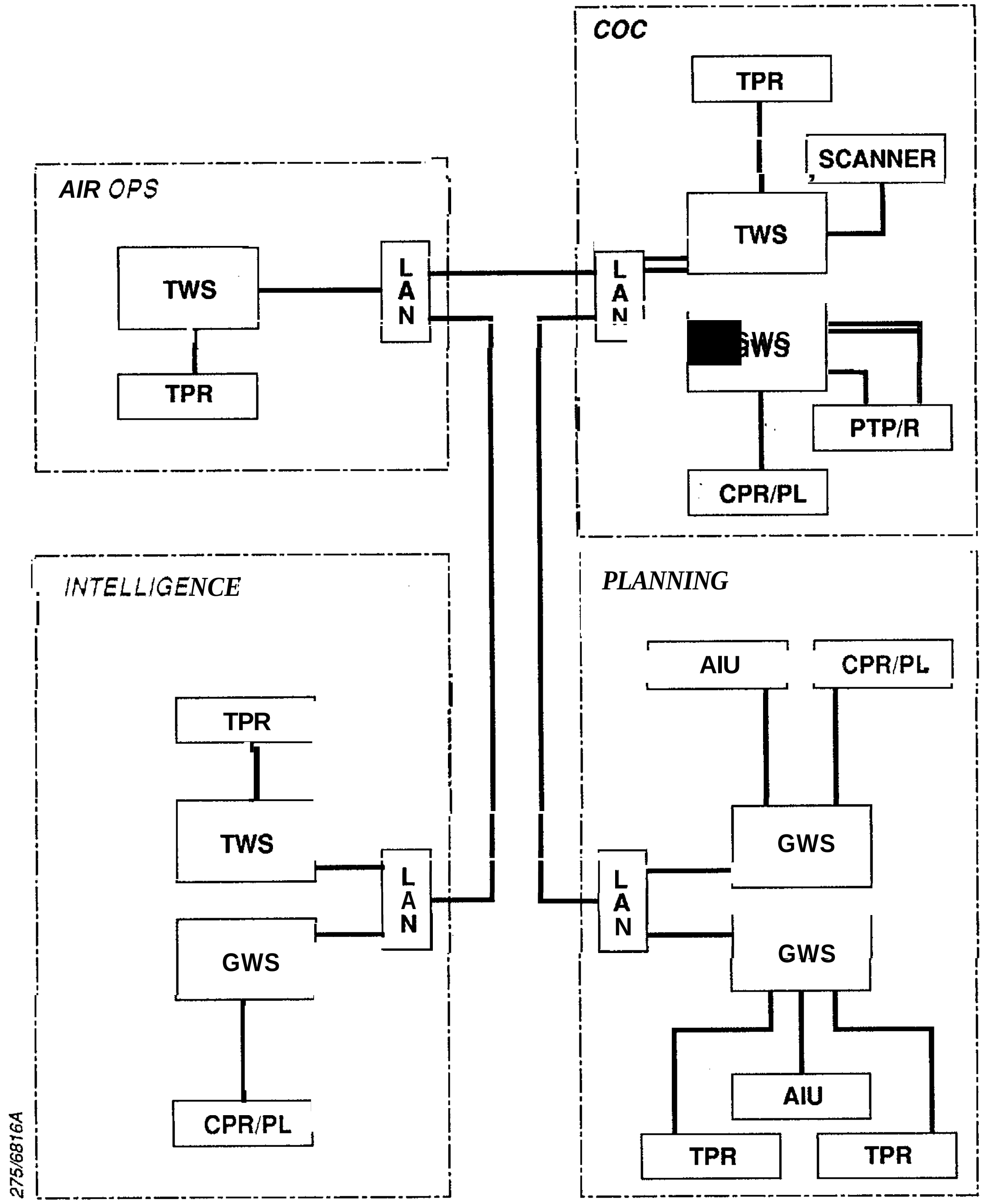

Fig. 2 Operating Base System Architecture

4. AMPS ARCHITECTURE

Earlier automated mission planning systems have tended to operate in a stand alone mode. The latest AMPS have been configured to include distributed databases combined with comprehensive communications to achieve automatic updates across a wide area network. Realisation of the AMPS architecture has also been driven by requirements for rugged equipment and resilient reversionary capabilities in the event of failures. Hardware solutions have therefore been configured with the maximum use of common equipment. At the same time, increasing use is being made of ruggedized commercial workstations which continue to offer powerful processing with Open Systems architecture, excellent reliability, reduced weight and ease of portability.

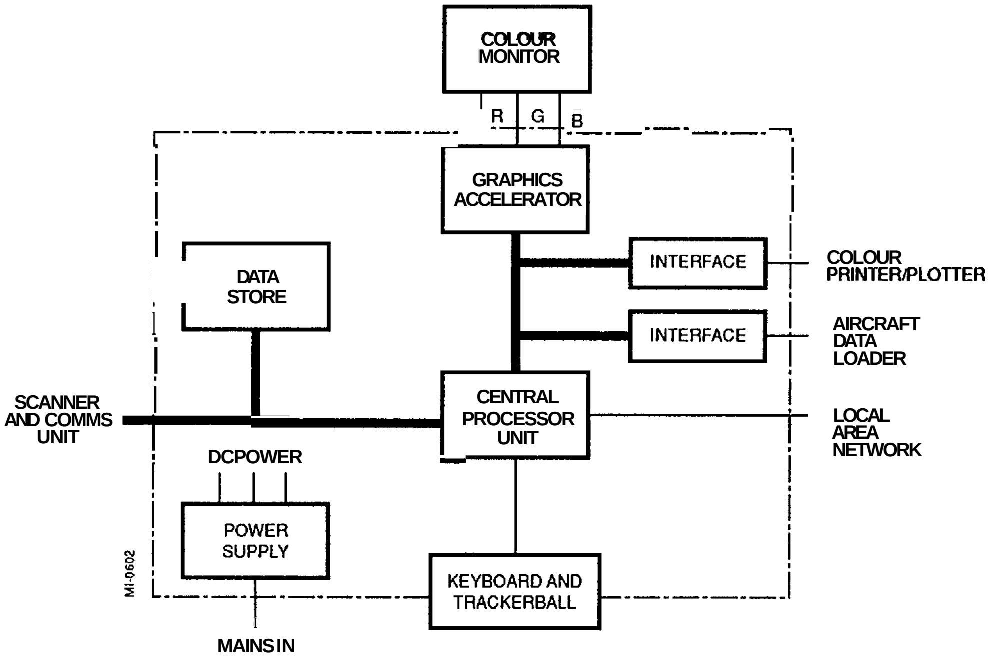

Fig. 3 Graphics Work **Station Schematic**

4.1 Graphics Workstation

A schematic diagram of a typical graphics workstation (GWS) is shown at Figure **3,** where it can be seen that the availability of fast processor boards and the essentially random access read/write technology of Magneto–Optical Disk Systems have led to revision of earlier arrangements of server processors and magnetic tape. The data distribution and archiving capabilities available in such graphics workstations offer easy and flexible access to the necessary mission planning data and the available processing power speeds the operator's activity. In addition the use of the X–Window Management System allows the provision of a convenient and easy to operate User Interface with a single screen. Liquid Crystal Displays (LCD) may be considered for this screen requirement, although their current display resolution may be lacking for the correct reproduction of detailed map displays. The diagram therefore currently includes a CRT colour monitor.

4.2 **Text** Workstation

A schematic diagram of a typical Text Workstation is shown at Figure **4.** Meant to provide those facilities which are fundamentally textual, the provision of text workstations ensures that Graphics Workstations are not performing tasks unrelated to the graphics processing requirements of mission planning. Business graphics facilities are well suited to Text Workstation use, as is the X–Windows System. LCD may well be selected for the display but CRT colour monitors may be preferred for commonality with the Graphics Workstation.

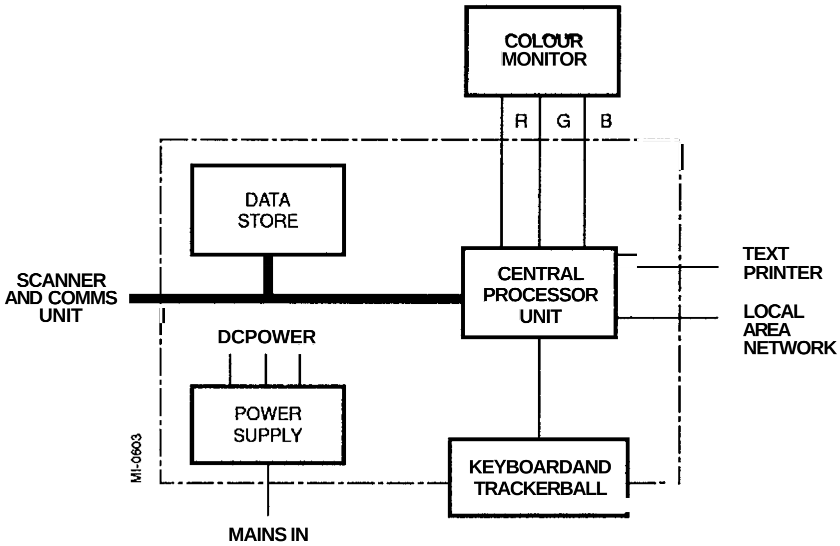

Fig. 4 Text Work **Station Schematic**

4.3 Communications Unit

The Communications Unit houses the Local Area Network (LAN) interface facilities. It typically comprises a protective housing and power supply system for a protocol changer module, containing a communications oriented microcontroller and digital signal processors with a range of downloadable protocols.

4.4 Printers

A rugged, good quality (say 300dpi) high speed (say 60 sec per A3 sheet) colour printer/plotter (CPR/PL) is required to produce hard copy map output for crew use in executing the mission. An additional reasonable quality (say 200 dpi) A4 text printer (TPR) is needed for the rapid (say 400 lines per minute) production of mission briefing and execution hard copy in text form.

4.5 Aircraft Interface Unit

The Aircraft Interface Unit (AIU) supports the electronic transfer of mission data to the aircraft and thus avoids the tedious (and potentially inaccurate) manual input of mission data. It also provides a convenient transfer route for detailed target maps and imagery in digital form where the aircraft is equipped with a Digital Map Generator (DMG).

4.6 Scanner

The presence of a scanner in the local area network allows the rapid scanning and input of target imagery and updated maps for use in the AMPS and onward transmission to any DMG. In the example shown at Figure 2 the scanner is positioned in the Combat Operations Centre but scanners can be more widely and locally positioned as the need arises.

5. AMPS DATABASE

The AMPS Database is an integrated combination of files and tables capable of holding the geographical and planning support data necessary for the production of mission plans. These data might typically be maintained on a fixed system disk under a system database management system. There are four major logical categories of data included in the database:

- Long term data
- Geographical Data
- Medium Term Data
- Short Term Data

5.1 Long Term Data

A number of data tables are maintained to hold static attributes with various dynamic data entities. Data entry takes the form of the Operator completing forms and tables. Long term data are not changed as part of the normal mission planning process and they are used by the mission planning facilities, not altered by them. Aircraft performance data, weapons performance data, Air Defence Unit (ADU) characteristics and the effects of defensive aids are included in these tables.

- Aircraft Performance Data

  The AMPS allows creation and alteration of aircraft performance data, normally derived from the aircraft ODM characteristics, in the form of static data tables associated with fuel consumption and drag calculations.

- Weapons Performance Data

  The AMPS allows creation and alteration of weapons characteristics. The static data tables include release speeds and drag characteristics. When defining specific characteristics for a particular weapon, tables and forms are presented to the Operator which are completed using the AMPS. The forms and tables represent a model of a specific weapon and include safe release conditions. The weapons may be divided into several groups, each group having several associated tables dependent on attack/weapon modes.

- ADU Characteristics

  The AMPS provides modules to allow the manipulation of ADU characteristics. ADU characteristics are the static attributes associated with an ADU site. Four convenient categories of ADU are:

  – Early Warning (EW) Radar Sites,

  – Anti Aircraft Artillery (AAA) Sites

  – Surface to Air Missile (SAM) Sites

  – Other Sites of Interest.

  The AMPS allows the Operator to define any number of different ADU types for each ADU category. When defining an ADU type a data entry form is provided allowing the Operator to specify a number of characteristics.

5.2 Geographical Data

In place of the paper maps used earlier, AMPS geographical data comprise digitized raster or vector map data at a number of map scales. The geographical data describe a specific area of interest and are typically held on a removable optical disk to provide storage for a large quantity of map data and to allow the area of interest to be readily changed. Additional imagery data, derived from sources such as SPOT, LANDSAT or scanned photographs, are also stored. Images which have been scaled and geo–referenced may be used during mission planning as if they were normal maps. In addition to map and imagery data, terrain elevation data is stored for use in intervisibility calculations and terrain simulation.

5.3 Medium Term Data

Medium term data are those which describe the conditions in the area of interest. They are updated on a regular basis and typically comprises information on forecast weather, friendly and enemy defensive dispositions, transit lanes, avoidance areas and communications arrangements

5.4 Short Term Data

Short term data comprise information directly associated with specific mission. These data are generated by systems users during planning. Major entities associated with this category are tasks, mission plans, predefined route segments, target details, deconfliction with other missions and coordination with associated missions

6. AMPS FUNCTIONALITY

Within the operating base system, the AMPS must provide the operator with convenient and rapid data access, processing and display. AMPS application software must therefore include modules to cover all phases of the mission planning cycle from receipt of a task, through the planning phases and eventually producing the mission output. Functionality is also provided to enter and maintain, within the AMPS Database, the data necessary to support the planning process. The software modules are structured and organised in such a way that:

- Modules can easily be added or replaced, allowing the system to be tailored to specific requirements.
- Operators can quickly access the necessary functionality, thus making the planning process more efficient.

To aid the Operator in using the system a comprehensive help facility must be provided. In addition the AMPS will normally use security and password control procedures provided by the operating system.

7. MAP CONTROL FUNCTIONS

Modules are provided to allow the Operator to control the information displayed on the map. These modules include map manipulation and overlay control functions. Specific functions provided include the following.

7.1 Scroll Map

The Operator is able to move the map left, right, up or down a set number of pixels. The Operator can change the number of pixels that a map is scrolled by using the 'Scroll Rate' facility which adjusts the rate at which a background map is scrolled.

7.2 Re-Centre Displayed Map

The AMPS enables the Operator to reposition the displayed map, without changing scale, by centering the map about the cursor position.

7.3 Change Map Scale

The Operator is able to select different map scales to be displayed, whilst maintaining the same geographical position. When more than one map image of the same area and scale exists the Operator can choose from a list of the available maps.

7.4 Map Catalogue

The AMPS includes the capability to list the contents of all the library in terms of available map images. The Operator is then able to select one of the maps from the contents list and display it. The Operator is prompted to insert the required storage device. The selected map is displayed, normally centred around the current geographical position.

7.5 Goto

Functionality is provided to enable the Operator to update the map display with a selected scale of map at one of the following selected locations:

- Target
- Take Off Base
- Return Base
- Operator Entered Lat/Long
- One of the user defined locations.

7.6 Brightness Control

The capability is provided to enable the Operator to control the brightness of the background map thus enhancing the contrast with the overlays.

7.7 Zoom

Enables the Operator to zoom a selected area of map. The zoom function is normally implemented through software pixel replication.

7.8 Overlay Control

Enables the Operator to display and remove specified overlay categories. Any combination of the following overlay categories can be selected by the Operator:

- Route
- Air Defence Units (ADU)
- Radar Shadow
- Battle Lines
- Transit Lanes
- Force Concentrations
- Route Annotation
- Avoidance Areas
- Chalk Board

7.9 Distance

A facility to determine the distance and track associated with two or more Operator specified geographical positions, selected on the AMPS map display. The distance function provides the following information:

- The length of the current leg in kilometers and nautical miles.
- The true and magnetic track associated with the current leg in degrees.
- The accumulated distance for all selected map positions in kilometres and nautical miles.

7.10 Position Information Display

The AMPS has the capability of displaying the following information associated with the map display cursor position:

- Latitude and Longitude
- UTM position
- Height of the ground above sea level, measured in feet and metres as calculated from the Elevation Database

8. INTELLIGENCE

An Intelligence Database management system is provided to allow the online entry and maintenance of dynamic mission planning support data.

8.1 Air Defence Units (ADU)

The system enables the manipulation of ADU. These are displayed over the background map to aid the operator when planning missions.

8.2 Transit Lanes

The AMPS includes the capability to maintain within its database safe transit lanes associated with the area of operation.

8.3 Avoidance Areas

Modules are provided allowing the Operator to define and maintain restricted areas. An avoidance area can be defined as either a circle or a polygon.

8.4 Battle Lines
Modules are provided to allow the definition and maintenance of such lines as FEBA (Forward Edge of the Battle Area), FLOT (Forward Line Own Troops) and FSCL (Fire Support Coordination Line).

8.5 Force Concentrations
Positions of both friendly and hostile force concentrations can be held in the AMPS Database. These are displayed over the background map to aid the operator when planning missions. Force concentration types are selected from a list of predefined options.

8.6 Chalk Board
The chalk board is an overlay allowing the planner to associate notes with a specific mission.

8.7 Target Library
Modules are provided to allow the entering of pre-defined targets. These target definitions are stored in the target library and can be selected when defining each new task. It is possible to edit, modify or delete target definitions, which might typically comprise the following information:

- Target Identification
- Target Position
- Target Type (eg Bridge, Airfield, power station)
- Target Structure (eg Metal, concrete, wood)
- Orientation and Dimensions
- Required Weapon(s) for Damage/Destruction

9. TEMPLATES AND DEFAULTS
To speed up the planning **process** the AMPS can be loaded with a series of route templates and operational defaults for standard use.

9.1 Route Templates
Facilities are provided to enable the, Operator to plan specific route phases independent of a task and save this information as part of a template library. The specific route phases involved include attack phase templates, formation templates and recovery templates. Templates are accessed through totes and can be saved, together with the Operator description, for recall and subsequent use in a mission plan at any time. Specific features associated with each of the template types are described below.

9.1.1 Formation Templates
A formation template facility allows the Operator to define lateral and trail separations for the following aircraft relative to the lead. The Operator can use the formation templates to define the formation to be flown along the route.

9.1.2 Attack Templates
The AMPS provides facilities to enable the Operator to select and position a target, IP, attack/approach/egress points and split/rejoin points for multiple aircraft. When an attack template is retrieved it can be attached to a target and rotated.

9.1.3 Recovery Templates
A recovery template allows the Operator to specify a touchdown/take-off position, the runway extended centre line, catchment range and angle about the centre line. The take-off and recovery zones will be displayed on the AMPS map. If required, landing separation times can be defined for aircraft in the final approach to the airfield.

9.2 Operational Defaults
Modules are provided to allow defaults to be setup that can be used during mission planning. The defaults allow the Operators to tailor the AMPS to their operating needs. Text fields on input forms are automatically filled in, by the AMPS, using the defaults information. This allows the Operator to work more efficiently by reducing the number of key presses. The information held in the defaults database might include such items as:

- Home Base Position
- Airfield Positions
- Squadron Identifier
- Aircraft Type
- Standard Initial Aircraft Fuel
- Aircraft Stores
- Standard Aircraft Speed, Height and Turn Rate

10. TASK DEFINITION
Modules are provided to allow an operator the enter information necessary for a pilot to plan and cmy out a mission. It is possible to enter, edit or print the task definition. The task details are entered via the keyboard and typically include the following information:

- Mission type.
- Required Time On Target (TOT)
- Number of aircraft
- Target characteristics

If the target specified is already defined in a target library, its characteristics should automatically be entered on the task form.

11. MISSION PLANNING
At the start of mission planning the Operator selects the weapon fit for each aircraft and the corresponding attack/weapon modes. The weapons available are defined in the weapon static data tables. The selected weapon fit and attack modes for each aircraft are shown on the AMPS text display.

The AMPS provides a complete set of modules for creating a route plan quickly and efficiently. Once a task has been defined, or recalled from the task library, the mission plan can be created. The user can then define the take-off, recovery, attack phase or transit phases in any order. Once the user has a complete mission it can be refined using the editing facilities and a flight plan produced. The mission can be saved at any stage and uniquely identified with a mission identifier to enable it to be easily recalled.

11.1 Route Planning

Once a task has been created, the user can recall it and begin planning his mission against it. The mission being defined is given a unique identifier and can be saved at any stage, together with a description. The user can retrieve partial or complete mission plans for editing and modification. The AMPS provides a facility for the calculation and display of ADU intervisibility shadows. These shadows can be used to show the intervisibility between Operator selected ADUs and an aircraft flight path.

The AMPS allows the Operator to plan routes for multiple aircraft. The Operator will designate a section of routing to be for the lead or following aircraft, or for all aircraft.

When planning for multiple aircraft the formation must be defined. The positions of the support aircraft in the formation can be defined by a lateral and trail offset from the lead aircraft. The AMPS will automatically calculate the position, fuel and timings of the following aircraft in relation to the lead aircraft given the formation being flown.

The route position and timings generated for each aircraft by the AMPS will automatically take account of tums. Crossover tums are normally applied automatically for changes in track greater than or equal to 30 degrees.

11.1.1 First Cut Route

This facility provides the Operator with a first cut route based on details entered on the Task Form, ie takeoff base, retum base and target location. It also takes into account intelligence information such as ADU types and locations, and makes use of any defined transit lanes. This 'first cut route' generation gives the user a fast indication of a route that avoids the engagement zones of the ADU's held in the AMPS database. This route is generated from the take-off point to the nearest safe air corridor, along this to the target and back along the nearest corridor to the recovery point. A comprehensive set of editing facilities is needed to allow the user to add, move or delete waypoints and to set speed, height and turn rates at designated waypoints.

11.1.2 Route Adjustment

Add, Move and Delete facilities enable the operator to modify the first cut route as necessary.

- Add Facility

  An "add" facility enables the user to create a new route section, add to an existing route section and to join two routes together. The waypoints that are added are given the current aircraft height, speed and turn rate values, which can then be changed at any time during the planning phase. Aircraft tuming circles are automatically generated for route sections that have an implied direction.

- Move Facility

  A "move" facility lets the planner select a waypoint for re–positioning. Once a point is selected it and any adjacent route legs are highlighted. The user can then "rubber band" it to a new position and fix it. Waypoint and route sections may be removed from the route by selecting an individual point or the ends of a section to be deleted.

- Delete Facility

  A "delete" facility enables a waypoint, leg, route section or complete route to be removed. The Operator can select a point/leg/route section interactively on the AMPS Map Display then delete the selected item. Turns are automatically re–calculated for the remaining route points.

11.1.3 Action Points

Points where an aircraft climbs, descends or accelerates will be designated as action points. These may be defined at an existing waypoint or at any point along a route leg. If a tuming point is designated an action point then the action will only be carried out after the aircraft has completed its tuming manoeuvre.

Once an action point is defined it may be moved. Those associated with tuming points are moved as a normal waypoint. However, movement of those defined along a route leg will normally be restricted to along the leg and between the two adjacent route points.

11.1.4 Remaining Fuel/Time Calculations

Fuel remaining and times are generated for individual aircraft as the routes are created.

- Fuel is calculated from the aircraft performance data given the initial takeoff fuel and payload. The fuel usage is shown accurately when the complete route has been planned but an approximation, using certain assumptions, can be made for route sections not connected to the base.

- Route timings can be deduced only when a route section has an associated reference time; either the take–off time or the TOT. However, where routes have no such specific time, the timing marks for the route can be displayed from 0 seconds to give the user an indication of the time taken to fly that particular section.

11.1.5 Route Optimisation

Route optimisation can generate a route that minimises exposure to threats. The optimiser generates a path, or possibly a number of paths, between two points within a user specified area. Two levels of route optimisation are available:

- Avoidance Level

  This generates a route which attempts to avoid threat engagement zones. Those which cannot be avoided are penetrated with the passage within the zone minimised. No account is taken of terrain radar screening. **This** level is quick to plan and can be used where no terrain elevation data is available.

- Optimised Level

  This generates an optimal path between the user defined points, taking account of terrain screening based on the aircraft flying height. In those regions where detection cannot be avoided, the path which minimises the risk of detection is generated. The optimised path considers detectability, defensive aids capabilities and other weighting factors attributed to individual ADU. It can also attach more importance to the avoidance of the engagement zone of an ADU even if this results in a longer path through a detection zone. Where many optimal paths are found, **the** optimiser module displays them all. This tends to form optimised channels showing how much latitude the operator has to vary his route.

11.1.6 Threat Analysis

Threat analysis can take two forms, threat intervisibility and risk analysis producing graphical and tabular output.

- Threat Intervisibility

  The intervisibility functions allows the user to view radar line of–sight shaded areas overlaid on the map display showing the regions, within the detection range of a threats, where the aircraft can be seen by those threats.

  This information is derived from the terrain data coverage of the area, the threat characteristics and the flying height of the aircraft. The user is able to select/deselect particular threats, alter the aircraft flying height or reduce the detection ranges based upon aircraft radar cross section and defensive aids capabilities.

- Risk Analysis

  Risk analysis is provided by the Route Risk Analyzer (RRA). The RRA takes a trial route specified by the user and assesses the risk to the aircraft from the various threats in the area. The RRA uses the threat intelligence database to obtain the threat details and characteristics. The user generates trial routes using a facility similar to the route editor and specifies the number of aircraft on the route. The RRA can produce graphical tables of results for each route, showing risk results for the combinations of threats, aircraft and routes.

11.2 Attack Phase Route Planning

A line of attack allows the user to specify a general aircraft run into the target. Once it has been positioned it may be revised as many times as required. Nomination of an initial point (IP) defines the final run in to the target and, when defined, overrides the original line of attack which is then readjusted to run from the IP to target.

11.2.1 Split/Rejoin

The user can define a split point, for a multiship mission and then plan the individual aircraft routes to the target. Once the aircraft have attacked the target they can be planned to regroup at a specified rejoin point.

A deconfliction facility is provided to assist in defining the split and rejoin points and the aircraft routes between the two. This allows the user to plan an initial route from split point to rejoin point and then refine it to meet any time constraints imposed on the mission. The first constraint is associated with the aircraft self damage. Once the lead aircraft releases its weapons over the target the following aircraft must ensure that there are safe time delays before entering the target zone. The safe time margin is derived from the weapons manual and depends on various weapon delivery characteristics. Taking account of these factors, the user can refine the route from the split point to the target to achieve the desired time difference. This facility can also be used to ensure that the aircraft rejoin at the required position within an accepted time interval. The egress route to the rejoin point can be refined by rubber banding until the time difference for the aircraft is zero at the rendezvous.

11.2.2 Weapons Planning

Modules are provided to support attack phase planning by simulating the release and delivery of weapons onto the target. The weapon fit for a given aircraft may be multiple or single type and the weapon types may be different for each aircraft in the mission. Each weapon type module determines the release point of the weapon, given the mode of attack (eg Laydown, Loft/Toss).

Safe release and effective strike of weapons are established. Using the selected weapons, the Operator can set various attack parameters (aircraft speed, run in height and attack height). The AMPS automatically calculates the release values providing impact speed/angle, release range and optimum position of release. The operator can easily alter the input parameters and observe the consequences, thus providing an easy to use "what if' facility. When the Operator is satisfied with the release values for the specific attack phase these values can be saved with the mission. The weapon release then takes into account the timings and fuel calculations for the route plan.

It is usual to include checks which allows the user to select only valid weapons and delivery mode combinations. The following are typical attack mode and weapons type combinations:

- Weapons Release in Loft/Toss mode

  This allows the planner to establish the optimum balance between the survivability parameters (release angle and pull–up distance from the target) and weapon effectiveness parameters (weapon impact angle and velocity).

- Retarded Weapon Release

  This module caters for weapons released in laydown retarded modes. The flight of these weapons are determined by a ballistic trajectory model operating on weapon drag data. The equivalent ejection velocity of the weapon from the aircraft is also used.

- Cluster Weapon Release

  This module caters for the release of Cluster Bomb Units (CBU's) in Laydown attacks. The weapon footprint dimension are calculated for the release conditions and can be displayed on the graphics screen.

- Stand Off Missiles

  Where long range stand off missiles are to be launched and finally guided to their target by means of a data link from the aircraft, it is necessary to coordinate the aircraft position and orientation with the missile arrival at the target. A module is provided which advises the range of acceptable aircraft positions and headings to ensure that a sight line exists between the missile and aircraft and that their respective data link beam patterns are within the required alignment limits.

11.23 Safe Escape

The system will produce a safe clearance time for the following aircraft in laydown attacks given the attack parameters of the aircraft. The critical time can then be used together with the route manipulation routines to ensure that the minimum delay limit is being met.

113 Route Annotation

The route annotation takes three forms, timing ticks, "doghouse" symbols aligned to the route and chalk board notes. The annotation can be placed on the completed route and forms an overlay on top of the map. All three forms of annotation can be printed with the map to form part of the output planning information.

- Time Ticks

  The time which forms the waypoint ETA will be displayed as timing ticks annotated on the route. The time ticks take two forms:

  – Route time ticks – Time ticks of a set interval, dependant on the map scale, along the whole route and indicating time in hours and minutes.

  – Attack time ticks – Time ticks of a set interval appearing on the 50K map between the IP and the target, indicating time to go to the target in seconds. **This** feature **is** used for detailed attack phase planning.

- "Doghouse" symbols

  This information will be an overlay on the map with the doghouse symbol being orientated to the route. The information present in the doghouse symbol will be the waypoint number, the track/bearing for the next leg, the distance to go to the next waypoint, the time to travel to the next waypoint and the fuel remaining at the waypoint.

- Chalkboard

  The Chalkboard facility enables the user to annotate the map with text, lines, circles and symbols.

12. MISSION CHECKING

Functions are provided for the Operator to check and validate the mission. Mission checking takes two forms:

- The automatic checking of the mission to find errors with respect to the mission plan, such as fuel shortages and timing violations;
- A visual check in the form of a 2D plan view simulation of the mission.

12.1 Mission Validation

On completion a full mission plan can be validated for the following:

- Fuel Shortages

  If the aircraft cannot complete the mission with the required amount of reserve fuel the mission will not be valid. The Operator will be alerted and the plan will be rejected.

- Take–Off Weight

  The total weight of the aircraft at take–off must not exceed the maximum permitted value (which is held in the Aircraft Performance Database). If there is a violation the Operator is alerted and the plan rejected.

- Routes

  A check is made to see that a complete mission has been defined with respect to the task and that the aircraft take–off and land at the appropriate bases and attack their designated target. If any of the conditions are violated the Operator will be alerted and the plan rejected.

- Action Points

  Checks will be made for action points which are not feasible, eg. a climb which cannot be achieved within the next route leg.

- Timing Violations

  A check will be made to ensure that the required takeoff time can be achieved for the required time over target.

12.2 Aircraft Deconfliction

Two facilities can be provided to check for aircraft confliction. These are the 2–D simulation facility and a 'target delay' facility.

- 2D Mission Simulation

  This facility provides the Operator with a simple and effective means of determining possible aircraft conflictions and errors in rejoin and attack timings.

  This function shows the aircraft travelling around the route in plan view on the AMPS map display. The aircraft in the mission are simulated by animated aircraft images which "move" along the route in user defined time steps.

  The Operator may start/stop the simulation, set the time step interval, step manually through the simulation either forwards or backwards, pause the simulation at any point and replay the mission from any selected waypoint. The facility displays the lead aircraft's mission time throughout the simulation.

- Target Delay

  The target delay facility allows the Operator to compare the safe escape delay time for following aircraft in a laydown attack flying over the same target, against the actual delay time as calculated by the AMPS. These times are presented to the Operator (on request) on the **AMPS** screen. The Operator may 'rubber band' the attack routing for the aircraft and the actual delay time will be dynamically updated. This provides the Operator with a flexible means of achieving the required delay time to avoid confliction.

13. MISSION REHEARSAL

A two dimensional terrain side profile can be displayed showing the aircraft flight profile, together with the weapon trajectory, over the IP to target terrain. This, along with the three dimensional **(3D)** IP to target run in, gives the pilot a realistic preview of the weapon delivery phase. Whilst the **3D** rehearsal is in progress the aircraft path can be displayed, in plan view to show map features of interest. The visualisation enables the pilot to gain confidence in the target approach and to make any necessary adjustments to height and direction to improve the planned flight path.

The AMPS creates a model of the land mass from the elevation database. The model can then be viewed as either a wire frame or smooth shaded image. The image can be further enhanced by taking into account the position of the sun or moon. The modules allow the operator to alter the displayed image by:

- Stepping forward, back, left, or right.
- Rotating the direction of view about a fixed point.
- Roaming as specified by the input device.
- Altering the viewing height.
- Scaling the terrain to exaggerate variations in height.

An automatic fly through facility is also provided which allows simulation of flight between two points (defined geographically or derived from a route plan) at either fixed height (above sea–level) or terrain following.

To assist the operator in interpreting the 3–D view the initial viewing position, initial viewing position objective and the angle of view are indicated on the background map.

14. MISSION PLANNING OUTPUTS

A number of hardcopy and electronic outputs are available to support the execution of the mission. The pilots may select any combination of the following.

14.1 Hard Copy Outputs

It is customary for the pilot to carry a Combat Mission Folder (CMF) of hard copy mission data. AMPS will allow the Operator to obtain this output for all or selected aircraft. The following outputs are typically available:

14.1.1 *Task Form*

A print from the text printer of the task form associated with the mission.

14.1.2 *Navigation Card*

A print from the text printer of a navigation card in a tabular form. The navigation card provides a flight plan tailored to the specific aircraft type. A navigation card is produced for each separate aircraft tasked to carry out the mission planned. Examples of the information which may be included in the flight plan for each waypoint or action point on the route **are:**

- Waypoint Identification
- Waypoint coordinate in lat/long
- Track
- Magnetic Variation
- Heading
- True Air Speed
- Indicated Air Speed
- Distance and Time to Each Waypoint
- Estimated Time of Arrival for Each Waypoint
- Actual Time of Arrival (left blank for in–flight entry)
- Fuel Remaining
- Remarks (left blank for in–flight entry)

14.1.3 *Route Maps*

A print from the colour printer of the route map associated with the mission for each aircraft and formation. To assist in the provision of strip charts a "strip chart template" can be included. This is positioned by the operator over the AMPS map display to indicate the position and coverage of the required strip prior to printing. The printed map is of an appropriate scale (eg 1:500,000) and typically includes the following information:

- Routedata
- Selected intelligence
- Route annotation
- Mission data

14.1.4 *Target Maps*

A print from the colour printer of the detailed target phase maps associated with the mission for each aircraft. Again, a "strip chart template" can be included. The printed map is of an appropriate scale (eg 1:50,000) and typically includes the following information:

- Target and Target Approach
- Selected Intelligence
- Route Annotation
- Mission data

14.2 Electronic Outputs

14.2.1 *Data Transfer Cartridge*

The AMPS would typically have the capability of writing mission data, created during the mission planning preparation, to **an** aircraft compatible Data Transfer Cartridge (DTC). The mission data is downloaded to the aircraft navigation/mission systems when the DTC is inserted in the cockpit receptacle. If the aircraft records data on this cartridge during the mission, the AMPS would read **this** data for display. Data that might typically be electronically transferred to the aircraft systems are:

- Flight Plan
- Waypoint/Offset Data
- Radio Presets
- IFF Mode Codes
- VOR/ILS/TACAN Presets
- Reversionary Waypoints

14.2.2 *Geographical Data Transfer*

Where the aircraft has a digital map display and where the aircraft or an on–board missile has a Terrain Referenced Navigation system, the AMPS and the DTC can be used as **an** interface to load map and terrain elevation data to the aircraft.

15. ARCHIVING

AMPS modules are typically provided to allow the Operator to Archive and Restore AMPS data. The data is written to a suitable storage device and enables backups to be performed. The following AMPS data groups are normally archived:

- Mission Plans – Tasking information and route data.
- All Intelligence data – eg ADUs and Avoidance Areas.
- Electronic Mission Data – Data previously recovered from the DTC.

During data recovery the Operator has the option to overwrite or merge the data, where appropriate, with the existing AMPS database. Intelligence data can only be overwritten whereas both Mission Plans and Electronic Mission Data can be merged or overwritten.

16. CONCLUSION

As outlined at the beginning of **this** paper, Force Level decisions create a pyramid of subordinate decisions on the separate elements required to achieve the Force aims. At each level the planning necessary to implement the decisions becomes increasingly detailed but over anarrower field. The information required to support **this** decision making and implementation must flow down from Force Level through the subordinate levels and also in reverse to keep the Force Level informed of progress, tactical situation and asset availability.

As the Gulf War demonstrated, the start of offensive air operations is likely to be a time of intense activity. Althoughearly missions will almost certainly consist of pre–planned sorties, following mission requirements will increasingly be dependent upon earlier results and enemy reactions and will therefore generate a peak of mission tasking, planning and execution activities. With the increasing ability of aircraft to operate by day and by night and in all weathers the mission cycle has the potential to become continuous.

At the Unit Level, the mission cycle begins with aircraft preparation and mission planning. The processes required for aircraft fuelling and arming have been increasingly automated and the times required have been much reduced. As aresult, the aircraft preparation phase tends to be the timing constraint on only the simplest of missions. The mission planning phase has therefore become an area of potential improvement.

It has been the practice that each mission was planned by the crews that were to fly it. However this has meant that the planning of a succession of complex missions during intensive operations has tended to impose timing constraints. Where time was particularly pressing and missions particularly complex, planning might have to starteven as theprevious mission was still being executed. Under these circumstances, and as long as missions were being planned manually, it was necessary to retain a core of experienced aircrew on the ground to complete and check the mission plans to the highest standards. This imposed extra manning constraints at Unit Level by limiting the number of experienced aircrew available to execute missions.

The automation of missionplanning described above offers more rapid completion of even complex plans and, by incorporating aircrew expertise in the automated processes, eases manning constraints, freeing experienced aircrew to execute the missions. However this speeding of mission planning requires the availability, careful arrangement and regular updating of a range of databases. This in turn implies the availability of suitable secure and reliable communications, both local and wide area. Communications have not been addressed in this paper but they are an essential ingredient in the full realization of AMPS potential.

In Flight Mission Planning In The "Copilote Electronique"

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1 SUMMARY

This paper aims at describing the functional aspects and the engineering guidelines of in flight mission planning within the french project called "Copilote Electronique".

This project is lead by Dassault Aviation with the support of French official services (DRET STTE) and involves many industrial and scientific partners.

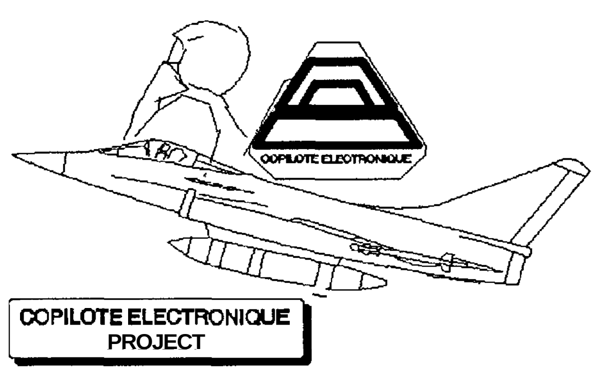
Emphasis is put on the in flight Pilot - System relationship and dynamic task allocation. **A** few words are said about knowledge acquisition methodologies and tools suitable with the development of a cognitive planning assistant.

2 INTRODUCTION

Since 1986 the french official services have supported several studies in the field of Pilot's assistance. The technical push of Artificial Intelligence and Knowledge Based System combined with the results of cognitive analysis of pilots activities resulted in the recognized need in the Guidance and Control community for more support to the Pilot in complex missions [1 Banks 91]. In France, it gave birth to the french concept called "Copilote Electronique" [2 Champigneux 89]. This assisting system relies on several in flight mission planning activities that are reviewed here.

The paper is divided into six main sections:

- In section **3** we review the results **of** requirements analysis of in flight mission planning for a future combat aircraft.
- In section **4** we analyse the advantages of a cognitive assistant approach other an automatic planing approach and we explain the "Copilote Electronique" orientations in that respect.
- In section **5** we describe the organic architecture and the proper mecanisms supporting the cognitive assistant approach of mission planning chosen for the "Copilote Electronique".
- In section **6** we adress the problem **of** dynamic task allocation between the Pilot and the cognitive assistant system in the field of in flight mission planning.
- In section 7 we give **a** short overview of the knowledge based development, process and its specificities in the guidance and control applications.
- In the last section we open to the possile future developments of in flight mission planning within the Copilote Electronique project.



Presented at an AGARD Lecture Series on 'New Advances in Mission Planning and Rehearsal Systems: October 1993.

3 FUNCTIONAL REQUIREMENTS OF PLANNING ACTIVITY

This section addresses the difficulties and requirements of an onboarded mission planning activity in a future combat aircraft.

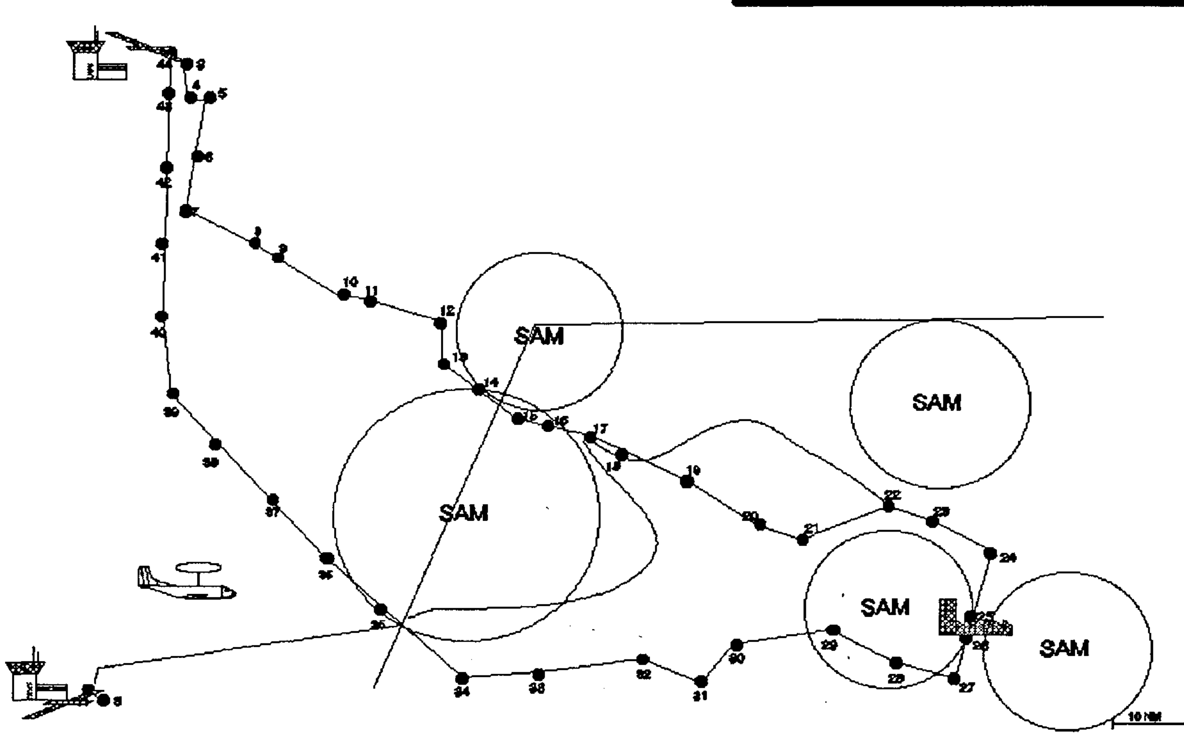
This analysis is driven by various studies conducted with the support of the french official services like, DRET **86.34407** faisabilité d'un Copilote Electronique and DRET **89.34565** Méthodes permettant le développement d'un Copilote Electronique.
It takes information from the various project of Pilot's Assistance presently known [3 Urlings 92] [4 Onken 90] [5 Mitchell 88] [6 Smith 88]. It is also the result of the cognitive analysis of pilots activities conducted by CERMA [7 Amalberti 92], and of the recent generic work on Guidance and Control Knowledge Based System performed by AGARD Working Group 11.

Conducting penetration missions in hostile territory has always raised problems of workload on single pilot. Regardless of aircraft configuration and avionics the planning activity is a very difficult task for the pilot in flight. This includes route selection, ECM employment (like activating and shutting down jammers, throwing decoys...), flight monitoring (following profile, respecting timing, handling communication with C3I...), attack planning and weapon selection... This overload problem has generally been solved by applying strict mission control rules over a very detailed ground based mission preparation.

It is recognised for example that in such Penetration Mission at low altitude and high speed within enemy territory, **a** pilot is following a strict time schedule with little possibilities to divert from it. For instance at an altitude of 300 to 500 feet and a speed of 500 knots only a few seconds of delay over the way points can be accepted. If such timing is not followed coordination between friendly ressources is in danger , the efficiency of weapon delivery is lowered and possibly, the firing of the aircraft by friendly ground defense will happen when crossing back the Front Edge of Battle Area (FEBA).

The extreme time pressure imposed on pilots of combat aircraft makes the planning activity very complex and dynamic. With such an extreme time pressure, in-flight planning could be considered as totally unrealistic, but it must be recognized that most of the time real missions will be perturbated by unexpected events. This leaves **no** choice to the pilot wh needs replanning.

PENETRATION MISSION



We have listed many of those unexpected events in the domain of aircraft ressources. One may mention engine failures, fuel leaks, sensor default... They are also numerous and frequent in the tactical domain. For instance one will encounter hostile aircrafts, unknown ground sites, electronic counter measures... There are of course perturbations due to the natural mission conditions such as weather evolutions, unregistrered ground obstacles... Finally one have to mention the possible human errors.

Therefore a strictly nominal execution of a mission plan prepared on ground is very unlikely to happen according to our experience of Mirage F1 CR or Mirage 2000 operations. Even simulation campains will show frequent perturbations with the necessity for the pilot to react by in flight mission planning. A recent Rafale simulated test of a sweep mission exemplified the interest of some pilot support in heavyworkload situation.

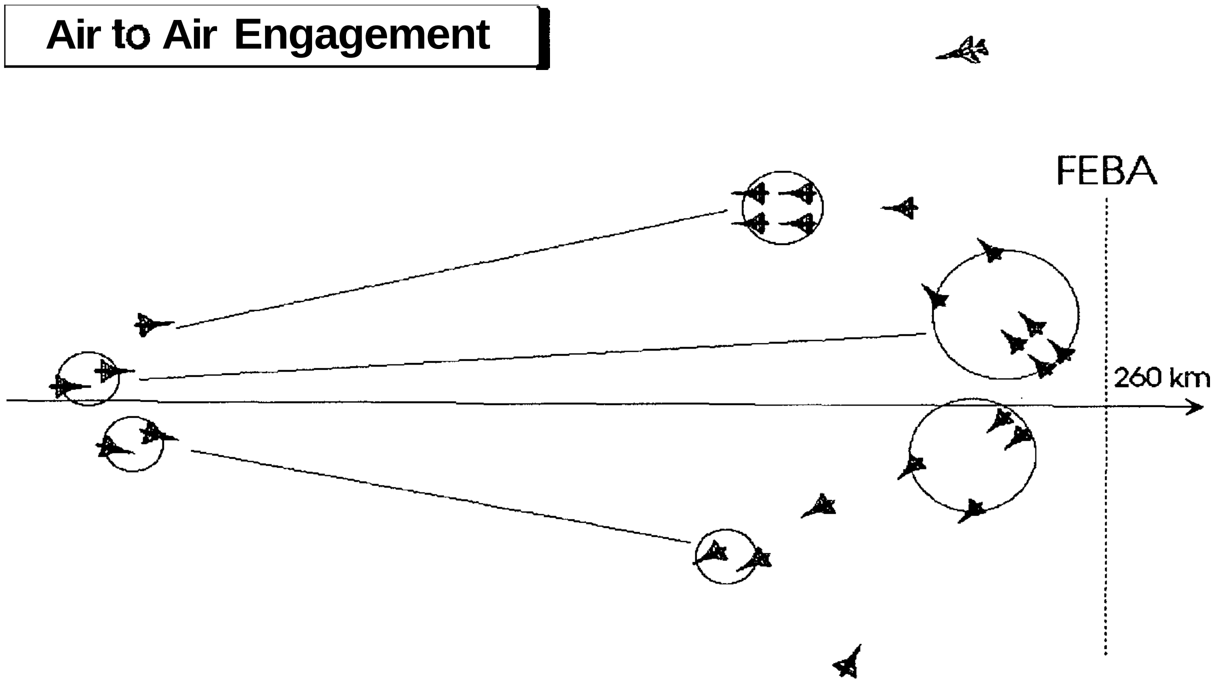
In such cases the functional requirements of pilot planning task ranges from flying activities, navigation, ressources management, information pick up, to tactical response elaboration.

For instance we analysed in detail an Air to Air Engagementduring an escort mission. In case of ennemy engagement, a pilot has to planify an adapted behavior to analyse the tactical situation including platform nanoeuver and sensor control. He needs to coordinate the friendly actions through communication with the penetrating raid bomber leader and with its fighter wingman. He exchanges tactical information, selects tactics, assigns target and he instantiates a proper offensive plan including weapon preparation, launch point calculations, flight path trajectories generation, evaluation of kill and survival predictions...

In conclusion of this section we can assess that a requirement for in flight mission planning is perceived in future low altitude high speed penetration missions and air to air escort missions (this is not to say that in flight planning is not needed on other missions such as air to air interception at high altitude but this analysis was not carried exhaustively within the scope of our project).

The planning task not only concerns navigation strategies but also tactical offensive and defensive management as well as aircraft ressources monitoring. These many planning concerns overlaps during active mission phases such as air to air engagement. Consequences of bad planification like taking wrong decisions, acting too late, or executing improperly the plan, are generally intollerable. It may result in a crash, or an unsuccessful mission, or the loss of aircraft and pilot ...

Air to Air Engagement



A single pilot with current avionics is unlikely to perform such in flight planning complex task without errors. A need for assistance is perceived , leading to increased autommation as well as planning support. We noticed during our analysis phase of the Copilote Electronic that there is a general preference for systems providing assistance in tasks such as calculating fuel, plotting routes, identifying risks.. . Pilots really care for better situation assessment in the planning process. This was well expressed by Major G.W. Breeschoten in his keynote address of Guidance and Control Panel 53rd Symposium [8 Breeschoten 92]_:
"I do not want the system to think for me, at least in the sense that it prescribes my tactical actions. It can to some extent think with me."

The french Copilote Electronique project is oriented toward a cogitive assistance as a consequence of this functional requirement analysis.

4 AUTOMATIC PLANNING OR COGNITIVE AIDING ?

This section deals with the problem of the level of autonomy best adapted to the in flight mission planning system.

In front of the increasing complexity of avionic systems and weapon systems it is certainly desirable to design systems capable of taking responsibilty of lots of planning activities. The present technological push, best exemplified by the well known knowledge based systems, expert systems, constraint programming tools, neural nets.. . leaves an open field to the dream of full automation.

Of course some caution should be taken in terms of feasibility for these techniques in real time avionics. As Wiener and Curry showed [9 Wiener SO], full automation can have serious drawbacks with a risk in the long term of having operators unable to conduct the missions. Therefore within the naturalist phase of the "Copilote Electronique" project, we cautiously analysed the tasks in terms of potential for automation and/or assistance. We based our first work on the guidelines of the AGARD advisory report on improved guidance and Control for the automation at the Man Machine Interface [10 AGARD 19].

These guidelines expressed that tasks requiring highly accurate responses, fastidious and repetitive actions, and exhaustive calculations are good candidate to automation. On the other hand, tasks requiring judgement, multi-sensory information gathering, hypothetical reasoning, contingency reaction.. . are best suited for a "Man in the loop" design.

Planning tasks are certainly of the second type. We structured those tasks like system reconfiguratyion, ressources scheduling, navigation, fuel monitoring threat analysis, threat avoidance, threat engagement, Command Control and Communication, sensor control and weapon management into thee main areas :

- System management
- Tactics managment
- Mission management

In the System area , planning is more often an optimization of fine grain plan in front of the flight parameters evolution and generalised state of the navigation and weapon systems (including faulty states).

In the Tactics area , planning is reactive . Threats are poping up as unexpected event and disrupt from the planified behavior established on ground during the preparation phase.

In the Mission area , the result of the mission preparation remains the guide for all in flight planning. The task here consists of local adaptations of the nominal plan, plan refinement in a precise context, choice of alternative plans.. .

At this stage of our design we have oriented our approach toward a human centered design. This was based on human factors evidences from the aviation history, which we briefly remind here.

When a computer system is always able to select the best solution for a problem , the current aviation policy is to couple this aid directly to the plane and keep the pilot out of the loop. The picture changes considerably when men are coupled to imperfect aids. Imperfect aid is the most frequent present (and most likely future) case for systems applied to tactical real time analysis. Here solutions need to be proposed rather than executed, and the pilot's ability to judge them must be maintained. The pilot also needs to be in the loop of reasoning to avoid "magic" behavior that can arise from blind belief in the aid.

Recent studies on human-decision support system identified a general principle of coupling that has obvious bearing on these solution.
- The less experience the operator has, the more interactions he will have with the system.
- The less the pilot's experience, the poorer the quality of his interactions with decision support systems and with optimal reasoning.

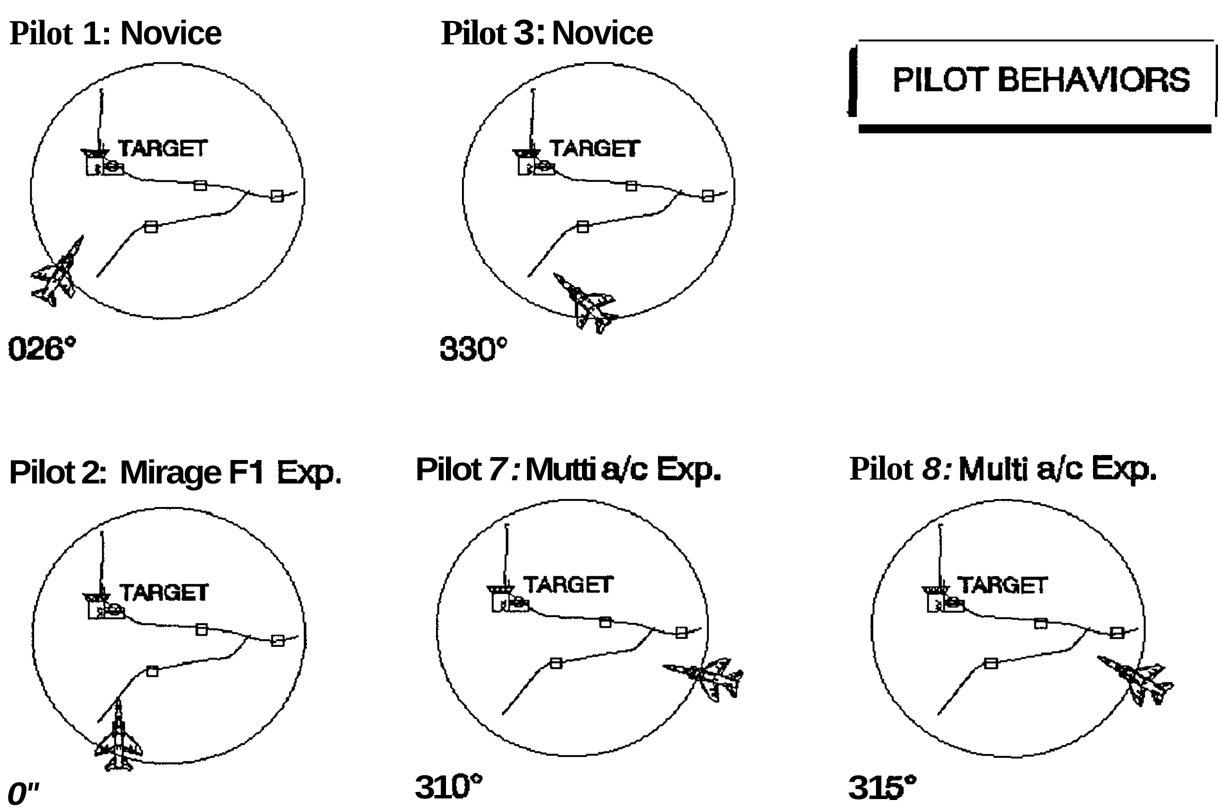
This principle can be expressed in similar terms : the greater the user naiveness as regards a support system, the greater the required commonality of knowledge and reasoning between system and user (glass box necessity).

However the glass box concept can be applied to different levels of requirements: the basic level consists in displaying informations in a natural way for the operator. "Natural" means quick understanding and resource free for the user. This level perfectly fits the concept of "Representation aids". Example of this are now numerous in the technical domains. For instance modern cockpits respecting this principle are termed "glass cockpits" (Airbus A320, Boeing 767/757).

The second level is more demanding. It consists in respecting the same reasoning process than Human when elaborating a decision . This, in contrast with the previous level, severly constrains the type of decision the system could propose. Nethertheless, this restriction could serve better the final user (namely the novice user) in dealing with the problem than any else optimal calculations. This brings to the notion of "Adaptive Aiding".

Of course, it is clear that a decision aid cannot be strictly identical to Human behaviour .This could not take sense as the respective abilities of Human and computer reasoning are very different (i.e. speed of calculation). Rather than imitating pilots planning the true challenge for a successful coupling of the Copilote Electronique with the Pilot is much more to tune the system solution according to the user degree of qualification and its current line of planning .

To support the architectural design of our Copilote Electronique we analysed in more detail the cognitive requirements revealed by CERMA field studies on Mirage Fl Pilot Behaviors.



These studies were conducted on pilot's cognitive activities during high speed, low altitude penetration missions over a four year period. The mission consisted in flying from an allied air force base , toward a target designated in advance. When reached , after approximately 1/2 hour flight, the target is treated for reconnaissance .The flight is as fast as possible and as low as possible to avoid being detected .The egress phase to the base is also at low altitude and on a different path from the ingres one. Mission preparation was made very carefully. Pilots spend more time in mission preparation (50 to 65 minutes) than in execution (45 to 60 minutes).

During this phase expert pilots and novices showed different cognitive process. Pilots with greater knowledge defined smaller navigation points and more candidate points to choose from. Novices tend to choose larger points making navigation easier but imposes severe constraints on the tactical side and give higher nautical mileage . This showed that pilots strategies depend on their knowledge of their internal competency and know how.

During flight these studies showed that the priority is given to short term activities like flight control . Pilots can only invest in medium and long term activities like navigation and tactical planning when the flight is stabilized for a sufficiently long period of time with correct parameters . During inflight operation the flight plan is never executed as defined during ground preparation. Deviations in route, timing and / or altitude are observed in and out of the context of incidental phases. Once again pilots strategies are varrying from experts to novices depending on their internal representation of competences [11 Amalberti 89].

Building on this experience we designed the Copilote Electronique architecture to keep the man in the loop . Planning is not performed to automate some specific task but rather to propose decisions on the same line of reasoning as the pilot .

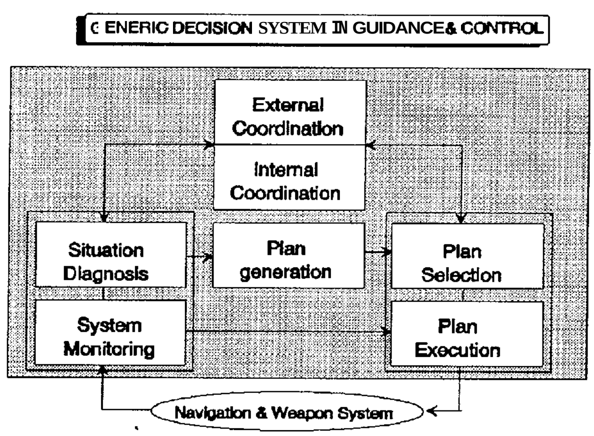
5 ORGANIC ARCHITECTURE AND PLANNING MECANISMS IN THE COPILOTE ELECTRONIQUE

In order to achieve the main objective of demonstrating the concept of a crew assistant for future combat aircraft it is necessary to organize expert entities that will perform the required functionalities of in flight planning.

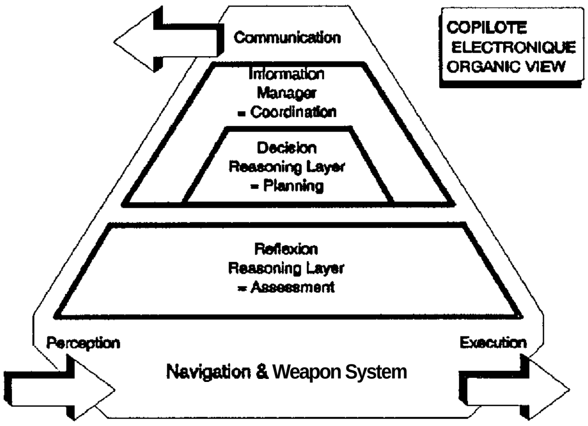
The Copilote Electronique project finalized such an architecture and this section gives a short overview of this architecture. It also address the technological needs linked with the necessary mecanisms of in flight mission planning in an assistant system.

The architecture of the Copilote Electronique is turned to a focused application i.e. single seater combat aircraft in an air to air escort role and/or an air to ground bomber role.

The top level organization of the expert entities in the Copilote Electronique is in accordance with the Functional Decomposition of Generic decision system in Guidance and Control as proposed by AGARD Working Group 11. The two main activities of Situation assessment and planning are represented by two layers of reasoning called "reflexion" and "decision" . The coordination activity is taken in charge by a specific entity called "Information Manager".



As we have seen the terminology of in flight planning covers a wide field of pilot activities contributing to the elaboration of a decision. Refering to system theory [12 Lemoigne 89] we can have a Copilote Electronique Organic View of the decision making systems by considering planning in connection with perception assessment communication and execution.



The planning reasonning layer will take entries from the assessment level. Those entries are problems , alarms, situation descriptions and hypotheses... This layer will perform plan generation and plan selection .

These generic architectural views can be instanciated on the specific domains of planning required by the decision process in combat missions. This limits the scope of the functionnalities and allows at this level of detail the selection of proper mecanisms.

The external world perception, the communication with other agents and the plan execution are not part of the Copilote Electronique responsibility but we can assume that these activities are present in the current Navigation and Weapon system (SNA) in which the Copilote Electronique is integrated .

The planning is split between what is called vertical assistance domains.

These vertical domains are:

-system planning,

-tactical planning and

-mission planning.

This decomposition is illustrated in the "pyramid" view of the Copilote Electronique Architecture.

Tactical planning is similarly split into

-air threat reactive planning,
-ground threat reactive planning and
-perceptive planning.

Information required by in flight mission planning consist in :
-vehicle performance information such as aircraft navigational accuracy, altitude measurement accuracy, endurance, equipment status including health evaluation,
-threats identifications locations and forecasted evolutions as well as friendly forces situation,
-mission information such as the target areas description for reconnaissance and attack, geographical data over the mission paths and weather data on mission legs.

Each vertical domain can in turn be refined into precise planning task (or task necessary to support the planning activity). This decomposition is summarised in the following list :

- System planning

. Planning the avionic systems reconfiguration.
. Scheduling of action & ressources according to the plan.
. Assessing efficiency and feasibility **of** the plan.

- System Evaluation
(in support **of** system planning)

. Monitoring discrete events.
. Monitoring continuous signals.
. Assessing real avionic systems states and dependability.

- Tactical planning
(similar decomposition of air threat reactive planning and ground threat reactive planning, at this point a finalized decomposition of perceptive planning has not been achieved)

. Planning tactics according to the threats.
. Scheduling actions and ressources according to the tactics.
. Handling conflicts among proposed tactics.

- Tactical assessment
(in support of tactical planning)

. Analysis of friendly & foe forces.
. Elaboration of forecasted evolutions.
. Assessment of risk/efficiency according to present plan.

- Mission Planning

.Selecting re-routing options accoring to the updated mission context.
. Planning new routes.
. Monitoring possible routes with quality estimates.
. Selecting current route.

- Mission condition Assessment.

. Mapping of pre-mission meteorological brieffing onto possible routes.
. Mapping of pre-mission geographical data onto possible routes.

The In flight planning mecanisms will be dynamically controlled based on a human-centered planning paradigm. This is realized in the Copilote Electronique through the following planning control modules :

- Pilot-Planning Assement.

. Monitoring Pilot actions.
. Assessing Pilot Intents.
. Assessing Pilot Workload.

- Assistant planning assessment.

. Monitoring information quality according to the plan.
. Monitoring current plannification according to the mission requirements.
. Monitoring the plan execution.

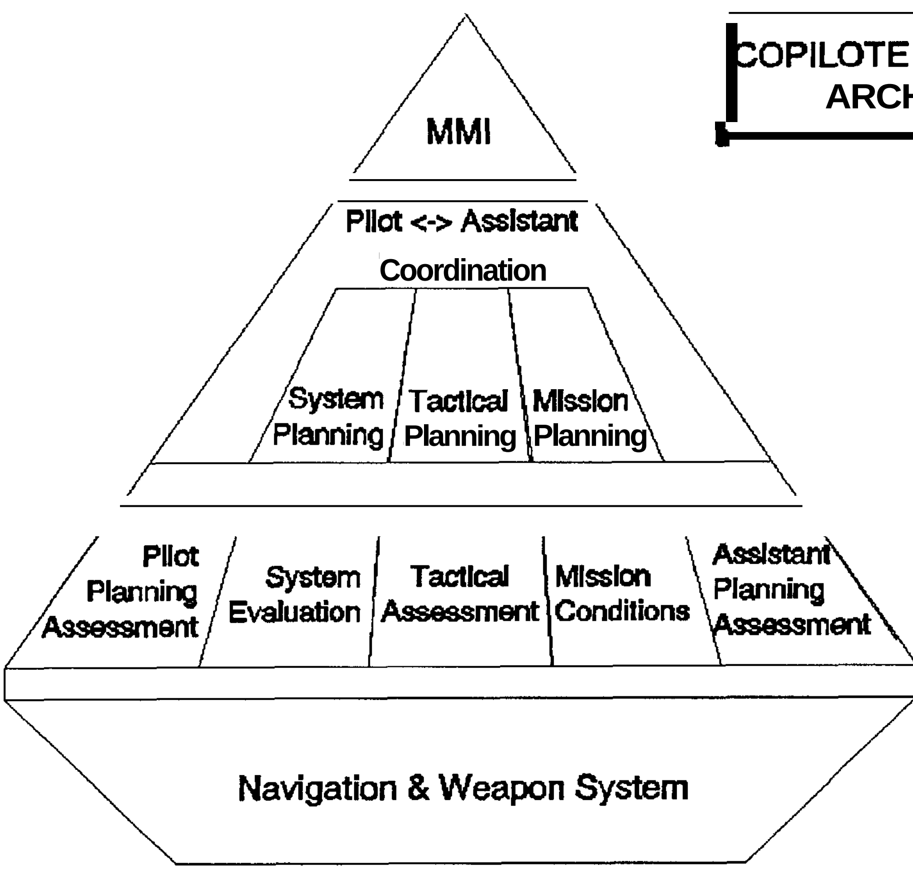
- Pilotc->Assistant coordination.

. Allocating tasks to man or expert agents.
. Monitoring MMI ressources.
. Solving conflicts among expert agents.

Each of those modules may require specific planning technics like A*, simulated anealing, dynamic programming, constraint planning, hierarchical planning, non linear planning, Multi-Agent planning, Model based reasoning.. ,

Our technical specification is driven toward a flexible heterogenous implementation paradigm. Our choice is to organize the modules in a multi-agent system using Distributed Artificial Intelligence techniques [13 Erceau 91]. Specificities of this approach are reviewed in section **7.**

COPILOTE ELECTRONIQUE ARCHITECTURE



6 DYNAMIC TASK ALLOCATION IN PLANNING

In order to maximize the mission efficiency and the cost effectiveness of operations, it is desirable to plan for a good management of the limited and valuable crew time.

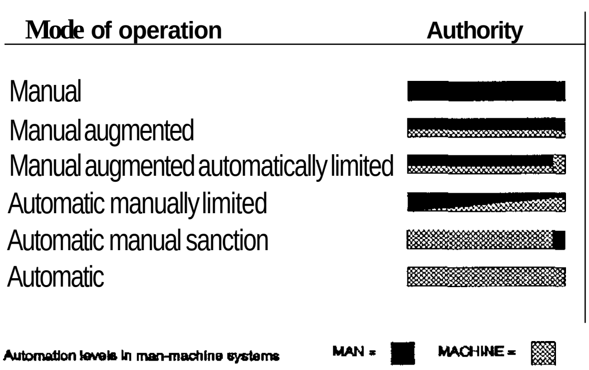
In flight planning in a guidance and control assistance can be designed as a manual system, an automatic system or as an hybrid solution between the two. An assistant planner is certainly of this third category.

A crucial question for the design of the planning assistant is that of task allocation between the pilot and the assistant.

In the line of a human centered approach our design is driven by an adaptive aiding concept meaning that task allocation will be dynamically performed in flight, based on the context and the pilot intents.

A classical guideline for task allocation is proposed by Seifert and Neujahr **[14** Seifert 87**]**. They structure the Man Machine relationship in six possible levels of automation.

Those levels are :



Automation levels in man-machine systems

In the copilote Electronique, planning will be using dynamically these six levels allowing an adaptative level of autonomy.

Adaptation in flight will be based on Pilot's meta-knowledge that we capture during the development phases. It will also depend on engineering constraints and contextual constraints.

It is not the place here to give the Pilots expertise about planning task allocation but general meta-knowledge can be mentioned.

For instance human intervention tends to be naturally focused on mission management rather than fine grain routine replanning. Pilots also take the lead to handle abnormal situations and will rather have supportive information to their own planning than disrupting plans during these phases. Pilots are reluctant to let a system planify critical actions leading to irreversible situations. On the opposite taking responsibility of some part of the planning burden during a complex air-to-air engagement seems acceptable.

In respect with contextual constraints our dynamic task allocation mecanism is essentially based on time pressure [15 Gilles 91]. But many other parameters will be taken into account. One can mention here criticality of the task, maximum quantity of information to process, quality of information to process, degree of problem structuration, human cognitive limitations, stress, fatigue, workload, coherence of allocations in time (hysteresis of the task allocation), coherence of allocations in view of pilot's qualification.. .
A special policy (or heuristic) is associated to each mission phase based on pilots preferences.
In any circumstances the pilot will be aware of the allocation policy.
This adaptive planning technique requires of course a strong capacity of intent inferencing [**16** Shalin **88**].

7 KNOWLEDGE BASED PLANNING SYSTEM DEVELOPMENT PROCESS

As we have seen in the preceding sections, the Copilote Electronique is a multi-expert system were planning takes very diverse forms. In such a system, the designer is faced with a multitude of choices to master the interactions of the cognitive agents.

This section presents the solution we developed for the Copilote Electronique program through a cooperative program with ONERA under a DRET contract (DRET **89.34347** architecture d'un systeme multi-expert embarqué d'aide a la decision).

As we described in section three, planning in the Copilote Electronique is split in five vertical assistance domains (system planning, tactical air-threat reactive planning, tactical ground-threat reactive planning, tactical perceptive planning, mission planning).

Each of those domains is decomposed in a situation assessment module and a plan elaboration module.

The coherence of the total system is insured by the three other modules (pilot planning assessment, assistant planning assessment and pilot-assistant relationship handling).

AS one can imagine the number of interactions between these agents is very large. This is the typical characteristic of a complex system [12 lemoigne 84]

The corresponding architectural solutions in terms of communication protocols, task coordinations, system granularity, ressources optimisations.. . are very difficult to master.

To implement successfully the Distributed Artificial Intelligence architecture of the Copilote Electronique, it is necessary to model and simulate the architecture very early in the project.

In the Copilote Electronique project, we decided to create a specific tool to master the architecture complexity.

This tool developped by ONERA is called **SAHARA,** a french acronym for "Simulator of heterogeneous architectures, agents and active ressources" [17 Barat 90].

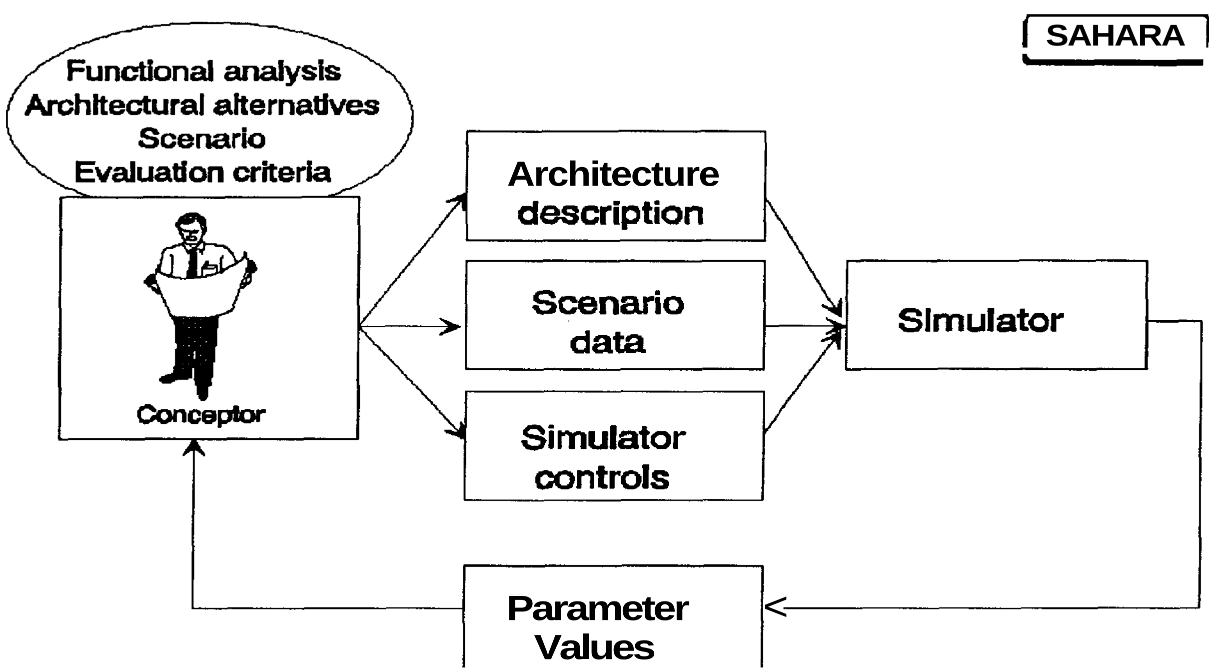
With this tool we describe the structure of the architecture at different levels.

At the functional level the system is viewed globally. The designer can verify that it will achieve the desired behavior and uses the proper information.

At the structural level, the designer express and analyse the system organisation. Functional agents can be decomposed and clustered in various ways. Data shared by, and/or messages passed from agents to agents, can be specified. This helps in mastering flows of communication and processing control.

At the virtual ressources level, processors, memories and channels are defined with their capacity and allocations so that the designer can get a feeling of the system performances.

Such a tool is essential to make measurements of communications between the planning agents. It helps in taking into account the processing time required by each planning process and the feasibility of certain task allocations in flight. It gives estimates of the memory size needed by the planning agents depending on the nature of problems. Our belief is that a complex adaptative system cannot be achieved with-out this type of iterative architecture refinement using a simulator.



8 FUTURE DEVELOPMENTS IN THE FIELD OF IN FLIGHT MISSION PLANNING

After a long design phase the Copilote Electronique is entering a software development phase. The planning domains are the main drivers of this development. They will be studied by various partners in a federative approach. Each partner brings to the project a specific background, with a high value knowledge of his planning field and mastering **of** appropriate planning mecanisms. This results in a very rich but heterogeneous multi-expert, multi-industrial planning system.

Our aim is to, not only reach a successful behavior in each planning field, but also to achieve a coherent assistant for in flight planning. Planning proposals will be demonstrated on a realistic full mission simulator. Special care will be taken to analyse interdependancies between the various plans and to respect the rules of a good man machine relationship. Expert pilots will give feedback on the quality and acceptability of the resulting planning assistant. According to their remarks the architecture, mecanisms and knowledge of the Copilote Electronique planners will be tuned.

Real time performances of the resulting planning system will be optimised next with the help of current technological progress (specially modular avionics and new software environment). Our belief is that the key of a successful in flight planning is more in the pilots cognitive abilities than in hardware/software evolution.

This technology is developped for the benefit of fighter aircraft of the year 2000 and beyond like future versions of the french ACT/ACM. It will certainly be proper for many types of aircraft and helicopters requiring Crew assistance to perform efficiently their complex missions. In the most generic view, the scope of such a cognitive planning assistant ranges the Copilote Section Electronique in the "time critical" decision aid systems.

9 REFERENCES

[1]S.B.Banks, C.S.Lizza,
"Pilot's Associate",
IEEE Expert V.18 pp18-29 1991.

[2] G.Champigneux, Y.Gaudry, A.Gilles, P.Nory, M.d'Orso,
"Vers une Intelligence Artificielle embarquee pour l'assistance au pilote: le Copilote Electronique",
Conference IA et Défense AVIGNON 1989.

[3]P.J.M.Urlings, E.W.Pijpers,
"Overview of Cockpit Technology Research and Development Programs for Improvement of the Man/Machine Interface",
AGARD MADRID 1992.

[4]R.Onken,
"Knowledge Based Cockpit Assistant for IFR Operations",
AGARD MADRID 1990.

[5]N.Mitchell,
"Computer Aided Tactics in the Cockpit",
AGARD COPENHAGUE 1988.

[6]D.D.Smith, M.Broadwell,
"The Pilot's Associate: an overview",
International AI Conference AVIGNON 1988.

[7]R.Amalberti, F.Deblon,
"Cognitive modelling of fighter aircraft process control: a step towards an intelligent onboard assistance system",
Int. Journal of Man Machine studies 1992.

[8]W.Breeschoten,
"Keynote Address, Air Vehicle Mission Control and Management",
AGARD Conference n°504 1992.

[9] E.Wiener, R.Curry,
"Flight desk automation: promises and problems",
Ergonomics 23,995-1011 1980.

[10]AGARD,
"Improved Guidance and Control Automation at the Man-Machine Interface",
AGARD report n°228.

[11]R.Amalberti, F.Deblon, A.Guengant,
"Advances in Navigation Support Systems Based on Operational Pilot's Heuristics",
AGARD LISBON 1989.

[12]JL.Lemoigne,
"La complexité est elle modélisable? La modelisation des systbmes complexes.",
Afcet systèmes, Dunod 1984.

[13]J.Erceau, J Ferber,
"L'intelligence Artificielle Distribuee",
La recherche 233 Vol22 pp750-758 1991.

[14]R.Seifert and H.Neujahr,
"Moding Strategy for Cockpit Data Management in Modern Fighter Aircraft",
AGARD STUTGARD 1987.

[15] A.Gilles, Y.Le Biannic, P.Montet, J.C. Heudin,
"A parallel multi-expert architecture for the Copilote Electronique",
Conference IA et Defense Avignon 1991

[16] V.Shalin, D.Perschbacher, P.Jamar,
"Intent recognition: an emerging technology",
Human-Machine interaction, Toulouse 1988

[17] M.Barat, Ph.Benhamou, J.Ferber , P.Nory,
"Design and analysis of multi-agent systems with SAHARA simulation tool",
COGNITIVA MADRID 1990

Mission Rehearsal in the SOF-ATS Program

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SUMMARY

The USAF SOF-ATS program includes both aircrew training and mission rehearsal elements. Recent advances in computer image generation and database generation have made possible the rapid database construction and scene realism necessary for mission rehearsal. This paper describes the development of computer image generator technology from that used in military flight simulation to meet the needs of the SOF-ATS mission rehearsal system.

INTRODUCTION

The failure of the American hostage rescue effort in 1980 highlighted the need for a mission rehearsal capability for Special Operations Forces aircrews. The device currently being developed to provide that capability must meet stringent requirements for rehearsal security, realism, and timeliness in responding to National Command Authority direction. Advances in computer generated visualization make it more possible than ever to meet those requirements [1].

The Special Operations Forces - Aircrew Training System (SOF-ATS) is a US Air Force Program which was awarded in July 1990 to Loral of Akron, Ohio. Evans & Sutherland Computer Corporation is a sub-contractor to Loral supplying ESIG-4000 computer image generators and display systems for the SOF-ATS program.

The SOF-ATS is a system of systems: an Aircrew Training System at Kirtland AFB, an Operation and Management Support System, and a Mission Rehearsal System at Hurlburt Field, Florida.

The training devices planned to be procured under the program include weapon system trainers for the MC-130E and H aircraft, and mission rehearsal devices with reconfigurable cockpits for the MC-130E/H, AC-130U, MH-53J and MH-60G.

This paper will describe the computer image generator and database generation system technology used in the SOF-ATS Mission Rehearsal System, but will not discuss the operational issues of mission rehearsal.

THE SOF-ATS MISSION REHEARSAL SYSTEM

The SOF-ATS Mission Rehearsal System will consist of five major elements: SOF Planning, Rehearsal, and Execution Preparation (SOFPREP), Mission Rehearsal Imagery Support System (MRTSS), Data Base Generation System (DBGS), Mission Rehearsal Devices (MRDs), and Mission Rehearsal Observation Center (MROC).

SOF-ATS mission rehearsal is a "many-on-many" simulation, with a high capability threat simulation. Several MRDs can be networked in a single scenario.

FLIGHT SIMULATION VISUAL SYSTEM TECHNOLOGY

Visual systems used in flight simulators employ computer image generators, which are special purpose computers designed to produce perspective scenes from a mathematical model of a pre-defined geographic area (known as the visual database). The most common, and most successful computer image generators use a polygonal model for their visual databases. These polygons are usually either triangles or planar quadrilaterals.

The visual database is a hierarchical structure of three dimensional objects which model the terrain

Presented ut an AGARD Lecture Series on 'New Advances in Mission Planning and Rehearsal Systems: October 1993.

and features in the gaming area. During simulator operation, the computer image generator retrieves from its database disks that part of the database which is potentially visible, then transforms the three dimensional coordinates of each potentially visible polygon into two dimensional screen coordinates. The polygons which cover each pixel are sorted into range order prior to the pixel level calculations which follow. The color of each pixel is then computed from the color and texture of the polygon or polygons which cover that pixel, and the current illumination, atmospheric, and weather effects. The pixel colors are written into a video buffer, then converted into analog video signals for output to the display system.

Flight simulation technology has been constantly driven by requirements from military customers for more realism and larger area visual databases. The visual systems used in simulation have traditionally been the least realistic element of the entire system.

Successful simulation for training of a specific task requires sufficient realism to cause "suspension of disbelief" in the trainee, i.e., he must be "drawn in" to the simulated exercise to such a degree that he believes, for the duration of the training session, that the simulated environment is real.

The degree of realism required for this "suspension of disbelief" varies with the training task. In general, more complex tasks require higher visual system realism. The most demanding application for scene realism is combat mission rehearsal.

Computer Image Generators versus Graphics Computers

Computer image generators differ from graphics computers in three important ways. A graphics computer will continue processing a scene however long it takes. The processing time is largely a function of the varying scene complexity which results in constantly changing processing times per field. In contrast to graphics computers, computer image generators must have a predictable and fixed processing time per frame in order to produce the effect of smooth motion in the computed imagery.

A graphics computer, unlike a computer image generator, is usually designed with demand paged virtual memory. This results in frequent "page faults" when memory references result in data which is not currently in semiconductor memory. These delays add to the non-deterministic scene generation times of graphics computers, resulting in jerky motion and difficulties in judging the effects of control inputs by the crew. A computer image generator is designed to ensure all data required for a scene is in memory before processing for that scene starts.

Finally, a computer image generator must be able to work with arbitrarily large databases with no reduction in performance, whereas graphics computers are often restricted to small databases which fit entirely in memory.

Thus while graphics computers are capable of generating perspective scenes which may look like those produced by computer image generators, they are currently unusable for mission rehearsal systems.

Computer image generators solve the constant update rate, memory access, and large area database processing problems by using a special purpose architecture which is not derived from general purpose graphic computers.

The simulator's transport delay, which is the time between the crew input and the change in the displayed scene resulting from the crew input, is designed to be constant. The computer image generator can process up to a fixed number of polygons per video field time. It has load management software which adjusts the scene content (in terms of the number of polygons to be processed) to produce the maximum continuous throughput without overloading, while ensuring that all calculations for each video field are completed before the end of the field time.

Computer image generator design ensures that any potentially visible object or area of terrain is loaded into memory before it is needed. This includes objects which are behind the current eyepoint position so that if, for example, a helicopter pilot were to turn his craft around, that part of the visual database would be in memory and processed to generate the required perspective scene. Since most databases are larger than the computer image generator semiconductor memory, software is provided to page the potentially visible database into memory as the ownship moves through the database. The paging algorithms use the ownship's current velocity vector to predict what part of the database to load from disk and what part already in memory can be overwritten as no longer potentially visible.

Computer Image Generator Performance

The performance of a computer image generator is often expressed in terms of the number of polygons and pixels produced per visual channel of imagery per video field. For example a computer image generator may process 3,000 polygons and 750,000 pixels at 60Hz to drive an interlaced display system. Here, one half of the displayed lines in the scene would be computed every sixtieth of a second.

However, great care must be taken when comparing these numbers to estimate relative performance between different computer image generators. Polygons are useful to estimate the visual complexity of a scene - intuitively the more polygons used the higher the scene density, thus more realism. However, scene density is more a function of how the available polygon capacity is used, which is dependent on the computer image generator architecture, the real-time software, and the database design.

Load Management

In order to provide a relatively constant polygon load to the image generator, regardless of scene content, load management software monitors each processing stage and makes adjustments in the subsequent scenes. These adjustments must be done smoothly in order to avoid distracting the crew with objects "popping" in and out of the scene. Objects which decrease in size to a few pixels on the display due to their range from the eyepoint can be faded out and removed.

The terrain surface and complex objects can be represented by fewer polygons at longer ranges, and most computer image generators have the ability to model the terrain surface and features at several levels of detail so that an appropriate representation can be rendered as a function of range. For example, a complex model of an aircraft may consist of several hundred polygons. At close range this would be an appropriate representation; however, if the aircraft were many miles from the eyepoint, it may only be one or two pixels in the displayed image and a much simpler representation with far fewer polygons would be appropriate. The management of level of detail, and the smooth transition between levels of detail, is a key discriminator in computer image generator performance, but one which is very difficult to specify. The scene realism required for mission rehearsal systems leads to high feature densities which makes effective load management a critical discriminator in system design.

Texture

Probably the greatest increase in scene realism has come from the development of texture for computer image generator systems [2]. Texture is a pattern derived synthetically, or from a photograph, which is applied to a feature, or to the terrain surface [3]. Without texture, the polygonal structure of the database was always evident, and it was very difficult to judge height and speed cues when close to the terrain surface. Texture modulates the polygon color resulting in a large apparent increase in scene complexity with no increase in the number of polygons.

With the new texture capabilities of modern computer image generators, it is now feasible to construct high resolution visual databases from imagery. Using techniques from photogrammetry, the geometry of the terrain surface, and of relevant features can be extracted. The processed source imagery can also be used for texture - an orthophoto can be produced to texture the terrain surface, and imagery of the tops and sides of objects can be used to texture the extracted features.

These developments in computer image generator technology have resulted in the high level of realism required for mission rehearsal. However, as database realism and complexity increases, the time to generate the database has also increased. A realistic database is of little use if it is not ready when it is needed. Therefore, some means to greatly reduce database generation time had to be developed in order to be able to use new high performance computer image generators for mission rehearsal.

SYSTEM DESIGN ISSUES

Technology for mission rehearsal systems has been developed from that used for military flight simulation. However, there are several important differences between systems fielded today for flight training and requirements for mission rehearsal systems.

Training Systems Technology

Training systems cover a range of performance from part-task trainers, through aircraft system trainers to weapon system trainers. These are designed to teach a specific set of skills, which by their nature change slowly, if at all. Therefore, the same training system, along with a limited set of training scenarios, can be re-used to train many aircrews over several years.

Fidelity emphasis of a training system is aimed toward replicating the response of the aircraft to crew inputs. Replication of the geography of the training area is often less important, and many training systems use a visual database which is a composite of terrain and features which are typical of operational areas, but represent no specific area of the world.

Mission Rehearsal Systems Technology

Mission rehearsal systems fidelity goals differ from those of training systems. Mission rehearsal devices are not designed primarily to train aircrew to operate the aircraft. The crew are already fully trained in the operation of the aircraft - what they need is training in tactics and familiarization with the terrain and features along the route and at the target area for one particular mission. This requires much more fidelity in the visual database, and allows for some lower fidelity, for example, in certain cockpit switches and controls.

The primary differences between mission rehearsal and training systems are the realism of the computer generated imagery used for the visual and sensor simulation and the speed at which the visual and sensor databases are generated.

A training system database can be built over a period of many months and then be used for several years to train crews in specific skills. A mission rehearsal database must be built in hours and will probably be used only once.

The new technology to support mission rehearsal impacts two primary areas: the database generation system, and the computer image generator architecture.

Database Generation

A simulation database is a mathematical model of the terrain surface, the two and three dimensional features which lie on the terrain, moving models, such as aircraft and tanks, repositionable models, such as SAM sites and thunderstorms, and the attributes of each feature for sensor simulation.

Most computer image generators require the database elements to be modeled from planar polygons, which are colored and/or textured. Texture is a natural or synthetic pattern applied to polygons to provide greater realism. An example is a model of a tree. If each leaf were modeled as a polygon, then the entire capacity of the computer image generator could be used to render one tree. If a photograph of a tree is used for texture, then a realistic tree can be modeled from six or eight polygons.

Likewise, small topographic features, which are not captured in the elevation data, can be represented with texture, either with a pattern which is typical of the local terrain, or with imagery derived from satellite imagery or aerial photography [3]. This approach saves polygons, while giving the crew more motion cues.

The terrain surface may be modeled from Digital Terrain Elevation Data from the Defense Mapping Agency, or from a Digital Terrain Model derived from stereo overhead imagery. Contour line following software can also be used with digitized maps to derive elevation information. The result is then resampled into a grid of elevation values.

Feature data may be obtained from cartographic sources, such as Digital Feature Analysis Data from the Defense Mapping Agency, or extracted from digital maps, or from map sheets that have been scanned. In target areas, and at waypoints, cartographic data may be too sparse, may not be current, and will lack sufficient feature height information to meet mission rehearsal needs. Digital photogrammetry can be used with high resolution imagery to extract features of interest in these areas.

Collection of feature data from a variety of sources requires a process to resolve conflicts between the data. These conflicts arise from cartographic license, different capture criteria and product accuracy between maps of different scales, and changes in urban areas over time.

Fixed features may be added to the database in one of two ways. Specific features, such as buildings in the target area, are modeled to represent one unique feature, whereas generic features such as trees and roads are referenced in the database as location, type, and orientation. A two or three dimensional model is then taken from a feature model library and instanced as indicated. These generic models may be re-used hundreds of times in a database, resulting in time and storage savings.

After collection and processing, the source material is converted into a common coordinate system, and organized into layers, from which the run-time formatting software converts the common correlated database into the run-time formats of the visual and radar image generators. The data flow through the SOF-ATS DBGS is shown in Figure 1.

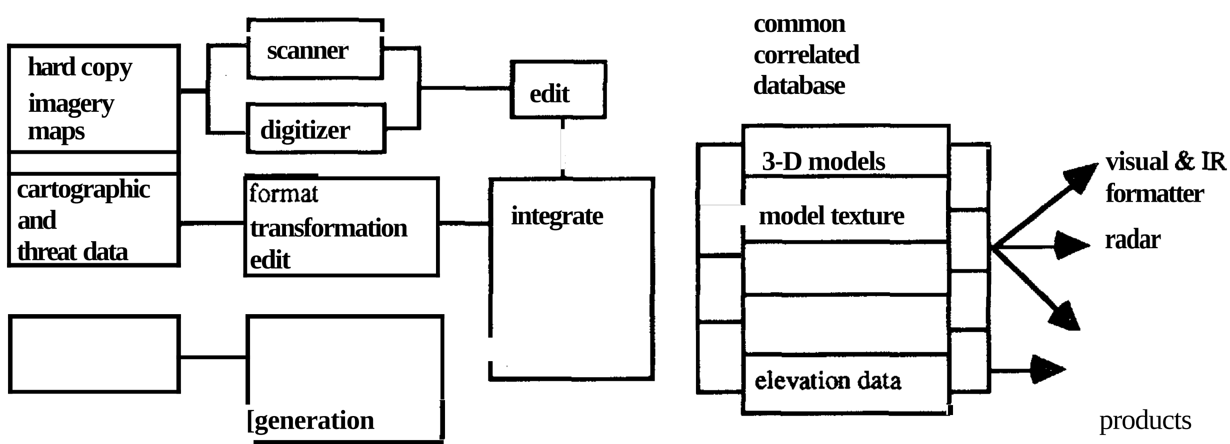
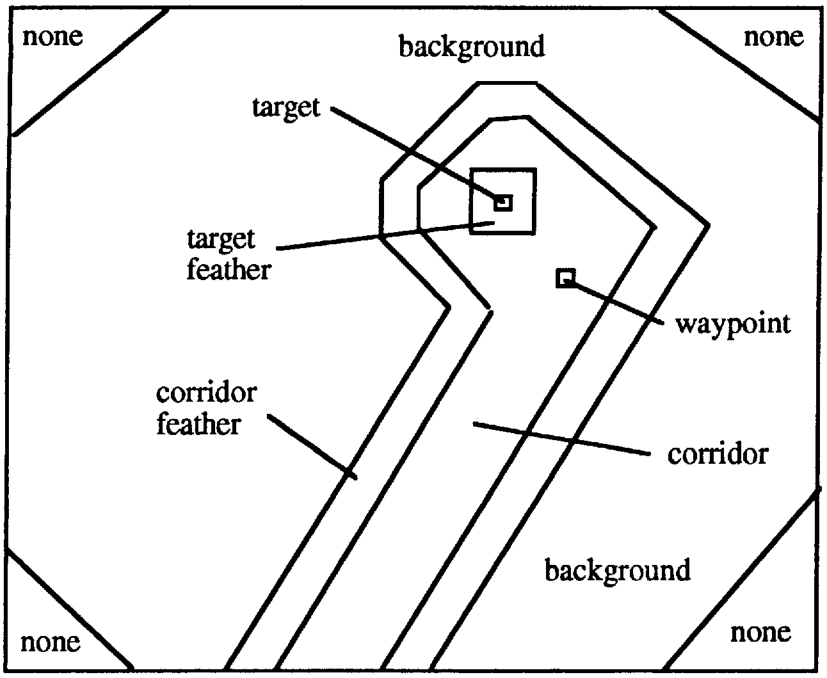


Figure 1. SOF-ATS DBGS Data Flow



Gaming area resolution is based on the mission profile:

- None (outside the gaming area)
- Background
- Corridor feather
- Corridor
- Nav and waypoints
- Target feather areas
- Target areas

Figure 2. SOF-ATS Database Resolution

A mission rehearsal database is typically built with varying resolution. The flight routes are produced from the mission planning system. Along the routes a baseline level of fidelity in terms of terrain accuracy, feature content, and texture image resolution is established. Around waypoints and target areas this resolution is gradually increased, and at the edges of flight corridors and into the background areas, the resolution is gradually decreased. This approach enables more database construction effort to be expended where it will make the most impact on the mission. There is little to be gained in high resolution modeling of the background areas, since there are no plans to fly there. Figure 2 illustrates a typical SOF-ATS database layout with varying resolution areas.

Finally the run-time formatted databases for the visual, IR and radar simulators are compiled from the common geographic database and the feature model library, and loaded onto the computer image generators. These databases are multiple gigabytes in size, and so transfer time is a major design concern.

The SOF-ATS Data Base Generation System is sized to produce a 500,000 square nautical mile database in 48 hours from the receipt of source data and the mission plan. Within the database are up to 25,000 miles of 20 mile wide flight corridors, up to 80 waypoints, and up to five target areas. This DBGS is the "engine that runs the SO-ATS mission rehearsal system."

Mission Rehearsal Computer Image Generator

Computer image generators designed for training systems have different requirements from those designed for mission rehearsal. If a database can be used for several years to train many different crews, then the cost of the computer image generator hardware is likely to be the most significant item in the overall cost of ownership of the system. However, if databases are only used once, and a new database is needed for each rehearsal, then the cost of database production will soon overtake the computer image generator hardware cost and will become the primary ownership cost. Therefore, a computer image generator architecture which simplifies database construction, while costing more initially, will ultimately save time and money. A lower performance computer image generator may require such lengthy database processing that a planned mission cannot be rehearsed in time. This would nullify any possible benefit of lower acquisition cost.

The computer image generator selected for SOF-ATS is the Evans & Sutherland ESIG-4000. This computer image generator was designed specifically to meet the scene realism and rapid database construction challenges of mission rehearsal. Instead of the traditional one run-time database, the ESIG-4000 has *four,* which are the terrain elevation grid, the terrain texture, the feature geometry, and the feature texture databases.

These four databases may be constructed in parallel, and may be updated individually as required. For example, it is possible to add new models to the feature database without modifying the terrain database. This computer image generator is able to handle many of the complex data transformations in the hardware, ***ut*** run-time, thus allowing the database itself to be represented more simply and economically.

The terrain elevation database is generated and stored as a multiple level of detail (LOD) grid. At run-time, the grid is converted into terrain polygons by the computer image generator. This occurs every video field time (typically at 60 times per second), for those grid posts which are potentially in the current field of view. The off-line conversion of DTED into the run-time format grid takes a few minutes per geo-cell (an area of one degree of latitude by one degree of longitude), compared to several hours to produce terrain polygons off-line for other computer image generators. For a typical SOF-ATS database of 170 geo-units, the time savings in terrain processing alone makes a 48 hour turnaround possible.

The ESIG-4000 computes twelve levels of detail for the terrain surface. This produces much better terrain accuracy than systems which employ only two or four LODs, and results in much better correlation between the visual, sensor and radar simulations.

After the terrain surface is computed for the current scene, the two and three dimensional features are placed onto the terrain surface by the computer image generator in a process known as conforming. This also occurs every video field time (typically at 60 times per second), for those features which are potentially in the current field of view. In conventional computer image generators, this process is done off-line in software, requiring very long compute times.

Simple features, such as trees or buildings, are modeled off-line around a local origin and are placed on the terrain at the indicated position and orientation. The ESIG-4000 range buffer computes the correct visual priority at the intersection of the terrain and feature polygons.

Features such as power lines are modeled off-line as though they were on a flat surface. At run-time the ESIG-4000 adjusts each line segment to produce the desired catenary curve shape.

Features such as roads, pipelines or forest canopies are subdivided at run-time by the ESIG-4000 along terrain polygon boundaries, and are clipped and adjusted according to the slope of the underlying terrain polygon.

If this feature placement were done off-line for every combination of terrain and feature level of detail over the entire database area, then the processing time would greatly exceed that allowable under the SOF-ATS contract.

The unique ability of the ESIG-4000 to move much of the time-consuming database processing from the DBGS into the computer image generator hardware makes rapid database generation for mission rehearsal possible.

CONCLUSION

Mission rehearsal systems represent the most challenging application of military flight simulation technology. The demands of the SOF-ATS program to be able to produce large geographic databases and start rehearsal for a mission within 48 hours has resulted in the procurement of a unique database generation system and computer image generator.

Recent advances in computer image generator architecture have enabled many of the most time-consuming database generation functions to be moved from off-line software into the computer image generator hardware, where these database computations are performed sixty times per second. New texture capabilities, much improved terrain accuracy, and high feature density have made possible the scene realism necessary for mission rehearsal.

ACKNOWLEDGEMENTS

The author would like to thank the USAF Aeronautical Systems Center / YTMS and the Loral SOF-ATS program office for SOF-ATS material used in the preparation of this paper.

REFERENCES

[1] Harper, J. K., "Development of a Rehearsal Device for Special Operations Missions", International Training Equipment Conference, Luxembourg, April 1992, p. 256.

[2] Bunker, M., R. Economy, and J. Harvey "Cell Texture - Its Impact on Computer Image Generation", 6th I/ITEC Proceedings, October 1984, Washington, D.C. p. 149.

r31 Economy, R., J. Ellis, and R. Ferguson, "The Application of Aerial Photography and Satellite Imagery to Flight Simulation", 10th I/ITEC Proceedings, November 1988, Orlando, Florida, p. 280.

REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's Reference	3. Further Reference	4. Security Classification of Document
	AGARD-LS-192	ISBN 92-835-0723-1	UNCLASSIFIED/ UNLIMITED

5. Originator Advisory Group for Aerospace Research and Development
North Atlantic Treaty Organization
7 rue Ancelle, 92200 Neuilly sur Seine, France

6. Title NEW ADVANCES IN MISSION PLANNING AND REHEARSAL SYSTEMS

8. Author(s)/Editor(s)	9. Date
various	October 1993

10. Author's/Editor's Address	11. Pages
Various	126

14. Abstract

Modem data processing technology with greatly enhanced capabilities is being used in both the airborne and ground-based segments of the NATO Air Forces. A key element in the interface between these segments is provided by the mission planning systems which are used to analyse, fuse and refine the information at air bases. This information is used to generate the mission plans before they are loaded into the aircraft's avionics system for use during the mission. The synergy of modem avionics systems and ground-based data networks cannot be fully realized unless mission data are provided effectively and rapidly to aircraft before the mission is commenced. Aircrew workloads must be minimized, both before and during flight, by the development of user-friendly planning systems which incorporate rehearsal facilities. The report from Joint Working Group 15, "Mission Planning Systems for Tactical Aircraft", will be used as the basis for this Lecture Series.

The aim of Lecture Series 192 is to present some of the design and engineering aspects of mission planning systems, with particular emphasis on human factors considerations. Examples of modern mission planning and rehearsal systems will be described.

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ISBN 92-835-0723-1

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