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PILOT'S ASSOCIATE DEFINITION STUDY

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Air combat operational and technological problems in the 1995 technology time frame are analyzed for application of artificial intelligence technology as developed under the DARPA's Strategic Computing Program. Operational missions are examined to identify those functions most critical for mission success. Applicable technology is reviewed including sources other than the SCP. A case is made for application of information processing architectural concepts new to airborne weapon systems, but matured in other disciplines over several decades, to accommodate AI technology. Such architectures are developed and reviewed. Onboard information processing hierarchies are developed to support mission requirements for both air-to-air and air-to-ground missions. These are then grouped into five processors, including a pilot/vehicle interface, to transition from the output of sensor signal processing to highly symbolic information for presentation to the pilot/crew. These processors are a Situation Awareness Manager to develop and maintain a current world model external to the airplane, a System Status Manager to perform the same function for the world inside the plane, a Tactical Manager to assess tactical implications of the world and make recommendations to the pilot for action, and a Mission Manager to evaluate mission plans vis-a-vis current situation and assist the pilot in revising plans as necessary. Artificial intelligence technology, both hardware and software, is reviewed and areas and degree of application of the technology to the air combat problem are presented and discussed. For purposes of evaluation of resulting application efforts, measures of effectiveness (MOE) and performance (MOP) are suggested and defined. An extensive glossary is included, along with two appendices describing a range of typical air-to-air and air-to-ground missions.				
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SUMMARY

Excessive data/information flow and increasing operational stress were among many reasons study of the potential for application of artificial intelligence technology to combat airplanes was initiated. Objectives of the study were to a) review and identify operational environments and pilot tasks required in the 1995 era and beyond, b) specify areas where artificial intelligence technology may assist the pilot do his job, c) review and assess AI technology status and specific applicability to the Pilot's Associate problem.

The major problem encountered was to determine the problem hierarchy from symptom to root cause so that technology application could be examined in a realistic 'venue'. Because of its high visibility, problems seen directly by pilots tend to get much publicity even if they are only indicators of much deeper problems. Separating out the salient facts was a significant study task. Techniques used included substantial combat pilot interviews, interviews with designers, analysts, and operational personnel other than pilots were conducted. But to a large extent, the study direction came from personal experiences of the authors in the field of air warfare for over thirty years.

Results of the study may be summarized as follows: to handle the data/information load anticipated in future systems will require a new approach to organizing information processing to more efficiently integrate the pilot into the system. Meeting this objective can be enhanced considerably by using artificial intelligence technology of wide scope, but particularly that technology under development by the Strategic Computing Program.

The authors found that combat systems, particularly single place airplanes, are designed and operated under guiding principle essentially unchanged from WW II. This in the face of explosive technology growth during the same period has resulted in a level of data/information processing required of the pilot simply beyond his physical capabilities. Attempts to reduce the data load by reorganizing cockpit real estate has merely shifted the type of problem facing the pilot, not solved it.

It became clear that while we espouse the position, "Let the system take over routine tasks and free the pilot for more cognitive tasks where he excels," the facts are that we now spend years of training every pilot to remove the requirement for him to think — the pace of air combat being so fast that no time exists to think — as much as possible must be reduced to reflexive behavior. In those less-than-crisis time aloft when the pilot can think, the "routine" workload is also significantly reduced.

Reorganization of the data/information processing system needs to begin as early in the data flow sequence as possible. Since this study did not delve into the heart of sensors and weapons, it assumed outputs from these devices as the basis for processing reorganization.

Furthermore, the impact of new technology and processing techniques was limited more to the data collection, processing and decision making part of the chain, with less emphasis on the role of AI in execution of commands.

A suggest form for the reorganization to processing was developed and presented. It includes several features borrowed from the human information processing system; namely, a continuum of processors loosely organized to permit decisions to be made at the lowest level possible where all data/information necessary for the decision are first available. In this manner, only those decisions requiring the pilot's experience and cognitive capabilities get to him -- unless he intervenes in the system. Hence, his workload can be reduced to acceptable levels given sufficient mature technology to carry out the lower level processing.

The stage is set for the Pilot's Associate Program to conduct design and development direct at resolving these issues.

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PREFACE

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The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressed or implied, of the Defense Advanced Research projects Agency or the US Government.

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SECTION 1

INTRODUCTION

This document describes the results of a requirements analysis study for the application of artificial intelligence technology to military combat aircraft. It is organized in five main sections covering:

1) Problem Discussion

- * Operational and Technological Issues
- * Problem Analysis
- * Architectural Considerations

2) Mission Analysis

- * Mission Selection
- * Mission Time-Lines
- * Difficulty and Importance of Tasks

3) Pilot's Associate Definition

- * Overview
- * Situation Awareness Manager
- * System Status Manager
- * Tactical Manager
- * Mission Manager
- * Pilot Vehicle Interface

4) AI Technology Assessment and Application

- * Software Assessment
- * Hardware Assessment
- * AI Technology Applications

To place these requirements in perspective, several appendices are included describing typical missions and scenario's of the 1990's. As this document is unclassified, specific details of missions and scenarios contributing to the requirements are not discussed. Hence, the body of the document deals with problems and issues on a generalized basis, with the appendices serving as contextual background.

Over the past 15 years, the pace of U.S. technology combined with increased Soviet threat sophistication and tactics presages an air combat environment in the 1995 era exceeding the human's coping mechanism. In the next ten years the Soviets and their allies will be capable of fielding a threat comparable to or exceeding our current capability. With their numerical superiority, the technical challenge is at hand. Since we rely on high technology vis-a-vis Soviet policy of numerical superiority, an ability to survive a major conflict depends on the pilots' ability to cope with his environment and make full use of high technology systems to control the combat scene. It has been postulated that this process can be significantly enhanced by incorporating artificial intelligence in the system.

To provide a common basis for discussion, a glossary of terms is included in Appendix A. In some cases, the definitions are narrow, in an English sense, but were generated for consistency and compatibility with other terms.

SECTION 2

PROBLEM DISCUSSION

Modern technology has increased the sophistication of tactical warfare to a point where, without assistance, human participation in complex systems could become counter productive. Even today we can produce systems capable of saturating a human's intellect and motor skills - forcing him into degraded modes of operation. Thus, the very technology created to help the pilot now threatens to cap his system's effectiveness unless more effective means are found to merge his skills with those of his system. Consequently, man's role in modern weapon systems must be totally reexamined with the objective of improving system operational effectiveness through a more intelligent approach to system design. It must start with an thorough appraisal of present system concepts with emphasis on those areas where the human's roles and limitations are constraining system effectiveness, and proceed to evaluate the impact of applying intelligent information processing concepts.

Of particular concern are limitations placed on system performance by time-bandwidth restrictions of the human information processing system. Events can move so swiftly in air combat that no amount of data compression alone can allow the pilot time to assess events and make decisions before the scene changes and new assessments are required. Under present conditions, as data quantity increases, processing time must be increased proportionately if the same quality output is desired. As an example of this phenomenon consider the interaction of humans with computer chess programs. In a normal game (three minutes per move or equivalent) human players can defeat the best computer programs, although it requires a world class player. If, however, the decision time window of the game is constrained to thirty seconds per move it becomes no contest - the computer wins easily.

Accommodating the human time-bandwidth limitation must therefore come by organizing information processing in such a manner that lower level decisions can be made reliably under stress by the system leaving mostly higher level decisions for the human to consider. Accomplishing this is a two fold problem; first, those processes selected for system processing and decision making must be amenable to machine intelligence technology of all types and, second, organization and presentation of results, as applicable, must be compatible with and communicable with the higher level human cognitive processes.

Simultaneously, the operational environment must be examined to identify those functions essential for combat effectiveness so that emphasis can be placed on incorporating artificial intelligence in the more critical system information processors.

The remainder of this section addresses four topics of paramount importance to the solution of these problems. These are:

- 1) The need for a thorough understanding of operational and technological issues including, but not limited to, machine intelligence,
- 2) An analysis and framing of the problem to place all major issues in perspective,
- 3) The requirement for sound and relevant system architectures in which to embed this intelligence and,
- 4) Explicit definitions of those major processes required to implement the most critical operational functions required in the 1990's.

2.1 OPERATIONAL AND TECHNOLOGICAL ISSUES

2.1.1 Operational Issues

In the case of air warfare, the root cause of limited pilot effectiveness under combat conditions lies in the environment. The immediate cause resides in our decreasing ability to deal with the root problem using conventional technology and philosophical approaches. To put the former in perspective, some of the driving operational issues are explored in this section. The ability to deal with its effects is covered in later sections.

Operational issues fall into one of two major categories:

- a) Operation under extremely hazardous conditions imposed by numbers and capabilities of enemy forces. For example, ten years ago, U.S. air-to-air missiles provided a significant force leverage over an enemy whose front line weapons were copies of outdated U.S. weapons. In the near future we will face weapons which reflect the effects of compromise of some of our most advanced weapons.
- b) Today very large quantities of information are, or can be, available to crews - quantities far in excess of their processing ability.

To put these issues in perspective, consider that at the highest level of analysis all combat missions consist of but three major phases:

- * Getting to within lethal range of the target(s),
- * Employing weapons effectively and,
- * Surviving.

- 3) To encourage "collegiality", a term borrowed from theorists of ecclesiastical organizations and their internal processes and relations to external functioning. That is, making decisions as soon as possible, at the lowest level where all needed information for a given decision has first converged. Finer divisions of levels reduce the probability of overburdening any one of them with too much decision-making.
- 4) To finesse the "hub" overloading problem of star topologies. All such configurations, whether in current tactical airplanes, computer data buses, or telephone switching networks, share this drawback.

In Figure 5 some interesting relationships are illustrated. Here maximum permissible IQ and criticality, reflected as priority demands on processing assets, are plotted against reaction time, that is, the time in which data and/or information must be processed and decisions made. Here we are using the expression 'IQ' as a general measure of intelligence, whether natural or artificial. In this context it merely indicates the degree of symbolic content present in the processing. Note that as reaction time eases, allowing more time for decisions, processor IQ may increase. But, as reaction time decreases, IQ can decrease. This relationship is common to larger knowledge bases associated with 'higher' intelligence and the associated processing time required to use such bases.

At the extremes of the scale are, for example, signal processors operating at gigahertz rates with close to zero symbolic content and, for example, a human analyzing social behavior patterns. Attempting to force low-reaction-time processing on an intelligent processor results in the task being either neglected or performed at radically reduced effectiveness. Here we have the reason pilots suffer rapid degradation in effectiveness under current conditions of overload: they are asked to perform under reaction times incommensurate with their intelligence.

In fact, normal intelligent modes of operation must be trained out of pilots for them to perform well. Pilots dogfight, for instance, almost purely by reflex and trained-in 'instinct'. This is one reason it takes several years to develop a competent combat pilot -- one trained to react to, not think about, situations.

In assigning processing tasks, it is essential to match the processor's IQ against task reaction time requirements. This applies not just to the division of tasks between man and machine, but also to the level of the machine's IQ as well. Prior to the contemplation of artificial intelligence in operational systems, division of tasks was based on a simple edict: let the man do what he does well and the machine do what it does well. But because machines had almost no intelligence, that left a large grey area man had to fill, even though he was too intelligent to perform many of the tasks well.

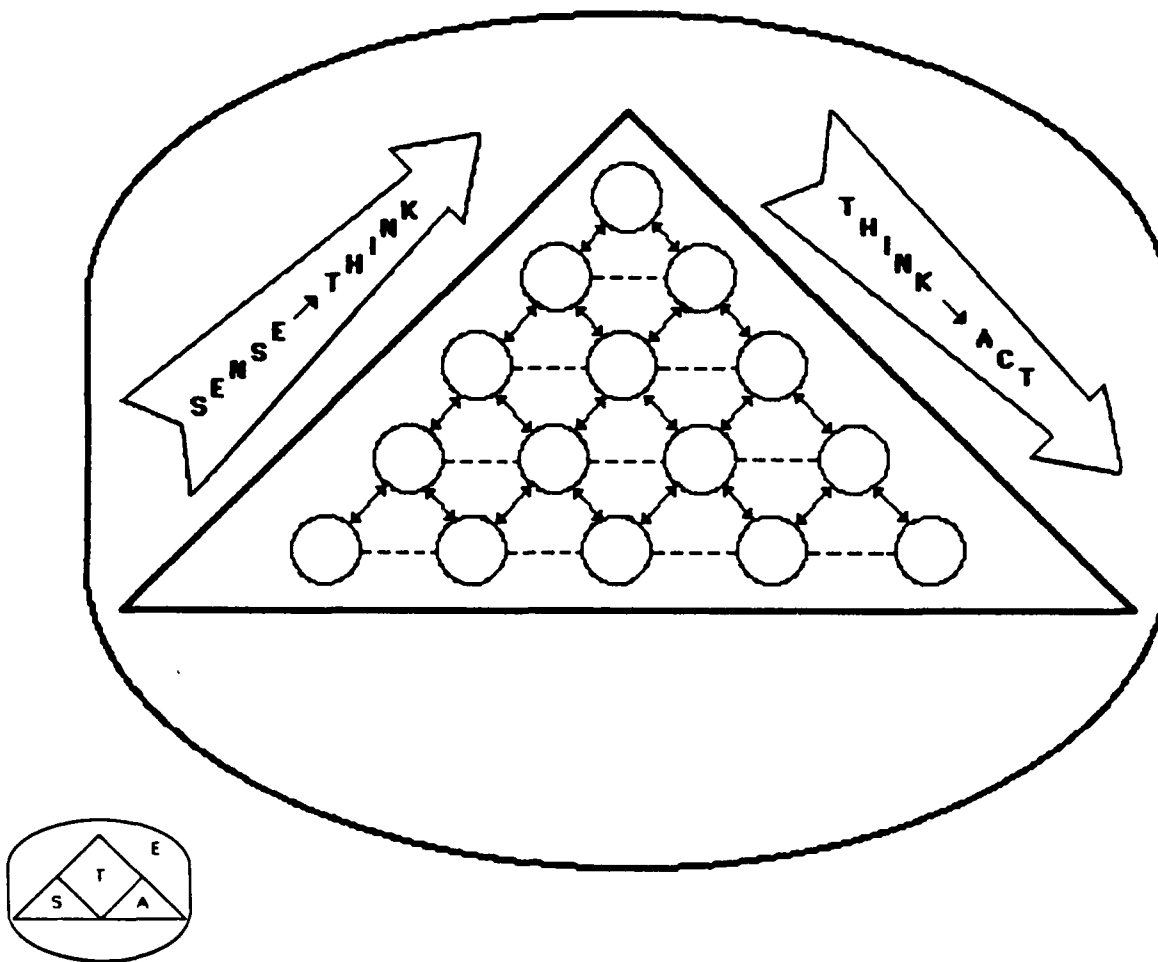


Figure 4 Hierarchical Data/Information Processing Architecture

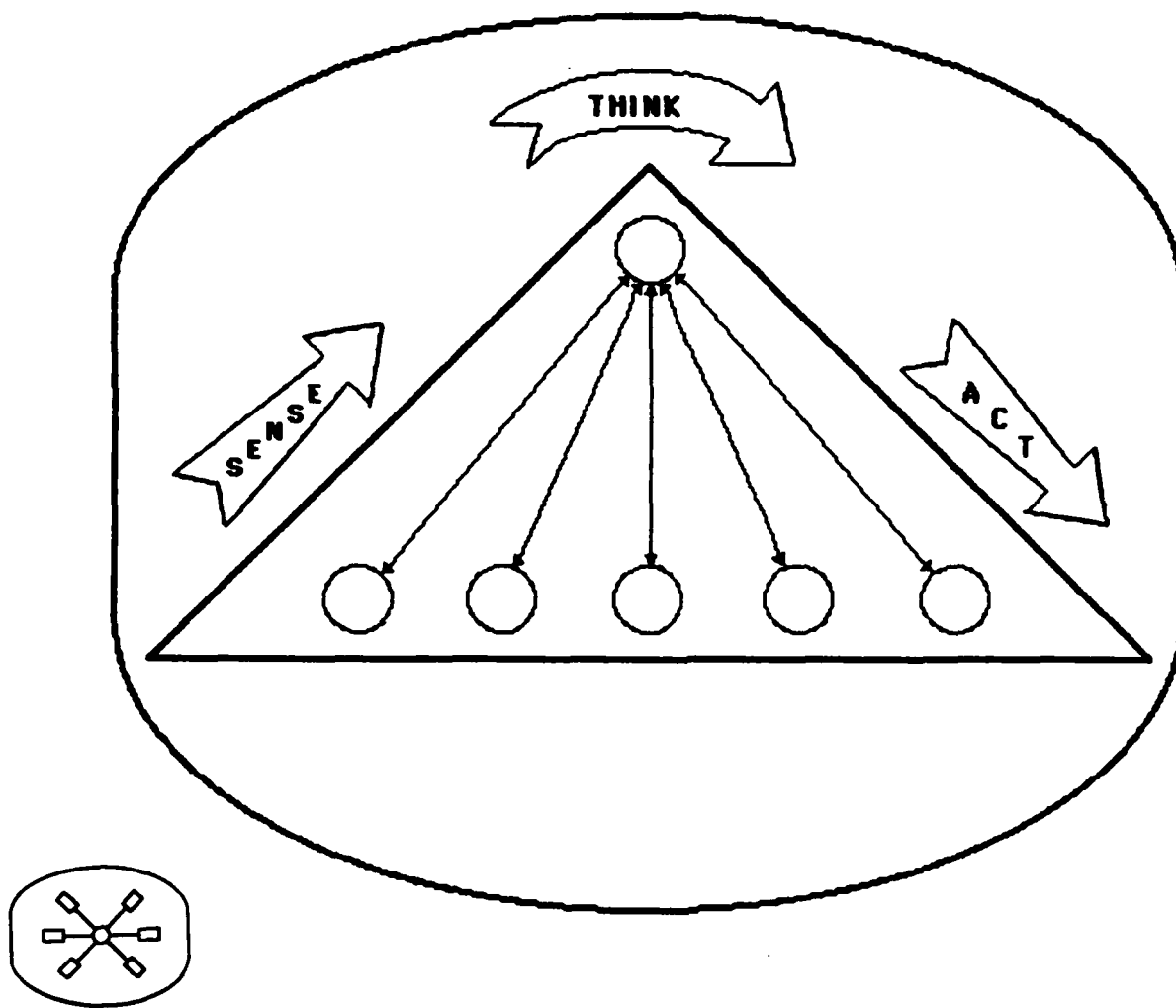


Figure 3 Star Architecture For Data/Information Processing

the system's process architecture able to support processing that is both general purpose and highly symbolic.

It is impossible to move from raw sensor data to cognitive processing in a single step, but how the transition is made dramatically affects system performance. Consider the arrangement shown in Figure 3. Here a simple representation of current combat airplane data/information processing organization is shown. At the bottom of the two level hierarchy are all of the airplanes subsystems, some sensor types other of the action subsystem class. But in all cases the path between any two, or any combination of them, must be closed by the pilot. As illustrated in the lower left-hand corner of the figure, this arrangement is known as a "star" architecture with the pilot at the hub. This arrangement was acceptable for airplanes of WW II and immediately thereafter. But as the complexity and number of sensors and effectors grew, the amount of data/information required to be processed by the pilot to make the system work became excessive. To handle the load, multiple layers of processing are required as illustrated in Figure 4.

In fact, four processing layers have been identified as typical of large-scale information processing systems. The functional level of system description naturally falls into a hierarchical structure by working backwards from the overall system goal through sub-goals directly supporting it, and on to finer levels of objective, task, function etc. The tangible, material level also falls naturally into a hierarchical structure (with five levels identified above). At lower levels, no individuality whatsoever obtains, so that aggregate statistical means are appropriate, if not unavoidable. Moving up the hierarchy reveals greater order, complexity, synergism, non-linearity and irreducibility.

It is, then, no surprise to find that processes also naturally fall into a hierarchical structure based on data bandwidth and its converse, symbolic content (IQ). At lower levels, we find signal processing taking input of many hundreds of mega-Hertz. As we move up in the hierarchy, bandwidth decreases and IQ increases through stages of data processing, information processing, and finally, symbolic processing. Even within any one of these four, there would likely be more than one level of processing. There are significant advantages to a relatively fine division of levels for processes. The primary objectives are:

- 1) To hold down fan-in. This follows the well-known maxim that more intelligent entities tend to "chunk" their input information to a higher degree than less intelligent ones. The maximum number of chunked items for humans is generally given as seven plus/minus two.
- 2) To keep processing gain at feasible levels. Here we use processing gain in its widest possible sense: the degree to which uncertainty has been reduced or made irrelevant.

The suggested use of AI, a sophisticated information processing concept itself, is in itself tacit recognition of the underlying problem. But not all systems on a combat plane are information systems.

The following discussion is aimed at putting the preceding in perspective through the use of some examples beginning at the highest level.

A system for the destruction of enemy resources may be called a weapon system for convenience. Its specific goals are destruction of a wide variety of airborne and surface installations and equipment, both fixed and mobile, both soft and hard. To achieve these goals, several objectives must be met. Targets must be found and identified and weapons employed in accordance with their operational capabilities and limitations. To achieve these objectives, the system must be capable of performing many functions (only a few will be discussed here, for simplicity's sake). Among these are the abilities to; reach the target quickly (quick reaction), to avoid being destroyed or damaged, to find and identify the target, to prepare and deploy weapons, to assess damage, and to return to operational base. Rather than consider a single process to achieve all these functions, a multi-process system is probably the easiest to deal with conceptually.

The first function alluded to above will be called simply transportation (implying transport of the weapons and supporting subsystems to the vicinity of the target). Processes that could be considered to accomplish this include crawling, flying, rolling, sailing, and so forth. Other design criteria not at issue here are used to determine which of these is best, all things considered. In each of these alternatives the process is a compound one. Process inputs consist of an energy source(s) and commands (speed, direction). The output is a change in one or more system state vectors.

The process of avoiding damage or destruction (surviving) has, as input, data from the real world, which, when combined with models of the world, result in a perception of the current situation. Outputs of the process include changes in detectable state (e.g., silent or emissive), changes in state vectors, employment of lethal weapons, etc.

The above examples should be sufficient to show how the rules of definition are applied in general. So far only high level systems and their characterization have been discussed; however, the ternary concept of function, process and form applies equally well at lower levels, and is essential to an understanding of the lower system levels (now referred to as subsystems). As indicated above, mission tasks (equivalently, system functions) vary considerably from mission to mission and present serious difficulties to anyone trying to assess them quantitatively. One must turn instead to the processes themselves: their relationships with one another, their overall structure and characteristics of process bandwidth, symbolic content, command level et al. There is an unavoidable variability and ambiguity of purely functional descriptions of systems which leads to seeking structures for

accomplishing the same function. The process is the second "view" of the system and may have limited direct correlation with the function.

Stated from the second view, the output of a process has some measurable effects on its world. Since this effect is defined as a (the) system function it can be stated that a function requires a specified environment to have meaning. An adjunct of the previous concepts is that performance is the act of a process accomplishing its function. Measures of performance are, therefore, measures of the ability of the process to accomplish that function. For example, uncertainty in position is a measure of how well the navigating process of our example system "performs" the function of navigation.

Processes can be divided into two general classes; tangible and intangible. Among tangible process we can identify at least five real subclasses; biological, chemical, electrical, mechanical, and nuclear (atomic) which are relatively self explanatory. Intangible processes number at least four major subclasses; signal processing, data processing, information processing, and cognitive processing. These require further explanation. Signal processing can be defined as any reversible process performed on raw (previously un-processed) signals. Examples include amplifying, side-stepping, filtering and gating. Data processing generally occurs after signal processing, however the degree or magnitude of the preceding signal processing, including none, is not a prerequisite for this definition. It is characterized by three traits - 1) the processing is irreversible, 2) the process results in a decrease in data bandwidth (a destruction of data) and, 3) an increase in symbolic intensity. <4> All three characteristics must be present for data processing to have occurred. Examples are detecting, smoothing, grouping, and transforming.

Information processing is defined as processing that increases symbolic content. It is further defined as the process of adjusting a model of the world to agree with observations. Its product is this adjusted or warranted world model sometimes called perception or situation awareness.

Cognitive processing acts on the perceived world to generate options by developing models of the world in the future through prediction of possible world states, evaluating these future models, and selecting the most apropos.

The third and last view of a system is the most common and if the formal view -- a description of the physical embodiment of the "tools" used to carry out the system's processes. Thus the classic statement for passive devices that, "Form follows function," must be modified for active systems to, "Form follows process which follows function."

Since modern combat systems are coming to depend more and more heavily on information processing, the key to better future systems, and the solution of present day system problems is postulated to lie in our understanding and implementation of such information processing systems.

<4>. A sensible destruction of data.

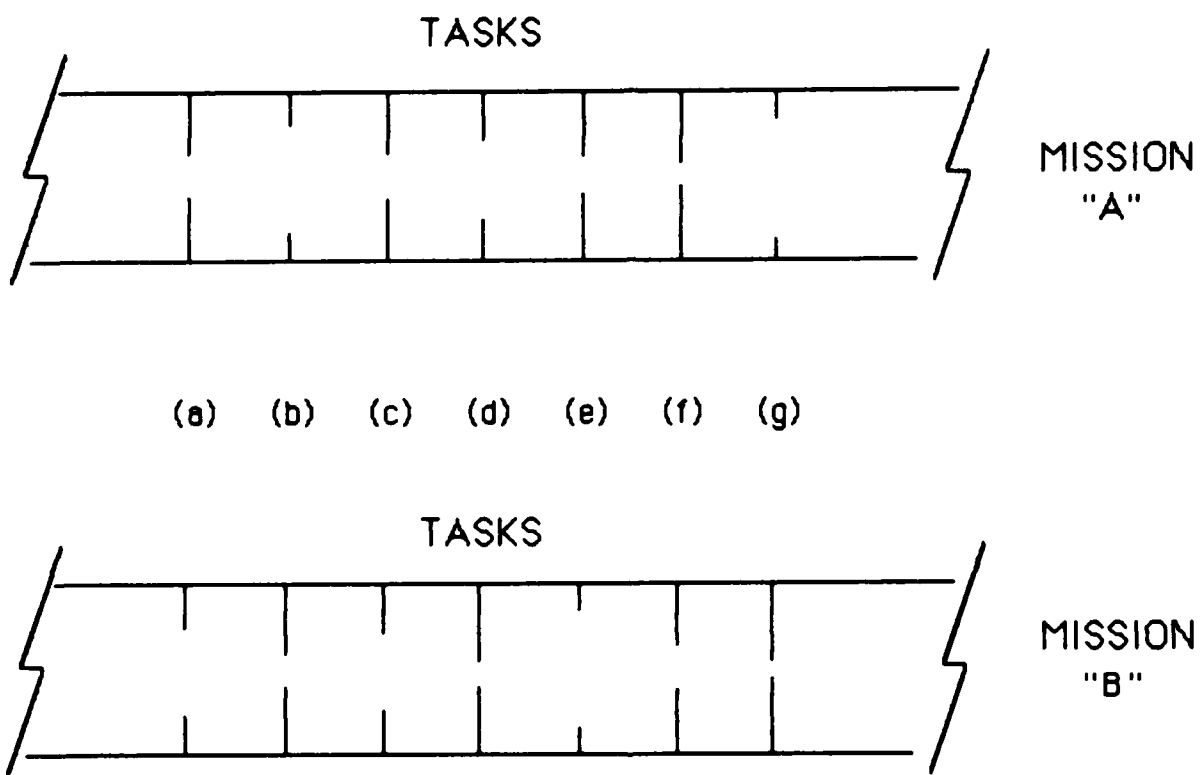


Figure 2 Variations in Task Impact on Mission Performance

comparable restrictiveness and if all the restrictions are successively removed, the greatest single gain in effectiveness occurs with removal of the last restriction.

Realistically, the last restriction is never be removed, but the concept helps to visualize relative importance of tasks and put their priority for refinement in focus. As an adjunct to Figure 1, Figure 2 shows possible variations in task complexity and relative importance from one instance of a mission to the next. The most restrictive (difficult) task in one scenario may be of little importance or difficulty in the next. Here one begins to see something of the fallacy of putting hard numbers on any one task or groups of tasks in order to rank it in importance with respect to all others.

In summary, the assignment of numerical values to tasks as a means of guiding development and application of technology most often derives from an inadequate understanding of the task and problem domains in question, and serves to replace understanding with a purely formal structure masquerading as reasoned analysis. A meaningful assessment of operational needs and opportunities for employment of AI technology will obtain only through a thorough understanding of operational issues, available technology, and the underlying problems.

In opposition to the classic approach, the underlying problem is proposed as one of inadequate architectures for dealing with massive information processing problems. The following section explores this in some detail.

2.3 ARCHITECTURAL CONSIDERATIONS

The preceding sections outlined and characterized some of the basic problems of air combat and its supporting technology. Consideration must now be given to methods for resolution of these problems.

Construction of a consistent framework for understanding the issues at hand requires acceptance of the definition of some fundamental terms and interrelationships. At the heart of such a framework is an acceptance of the definition of three different views of an information processing system, <3> Function, Process, and Form each serving a specific purpose.

Function is defined as a measure or description of the interaction of a system with its environment. It may also be viewed as the effect a system's action has on its world. It is an independent view of the system and may or may not have any direct correlation with the other views. For example, consider a system (X) whose "function" is navigation. In this case, the process underlying navigation is called "navigating." There are many different ways of navigating, each involving different variations within the process itself, but all

<3>. Not necessarily limited to information processing, but any processing system.

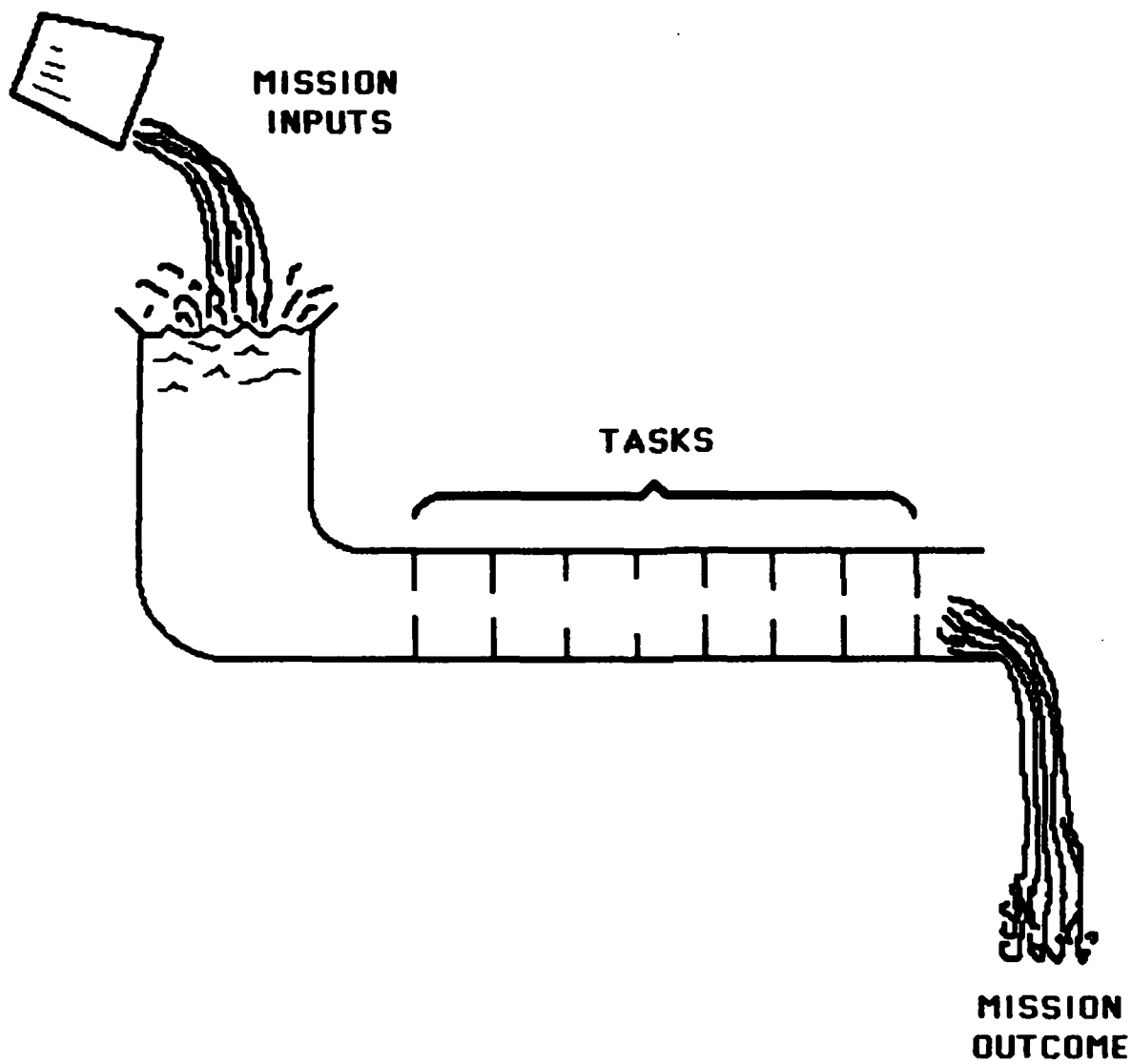


Figure 1 Mission/Task Relationship

to correct the problem. If the problem is human, then various alternatives are available including better or more training, better "human factors," adding crew members, and different allocations of tasks between man and machine -- or any combination of the above. It is suggested that in the case of the Pilot's Associate, these techniques are insufficient. The following analysis addresses this point and identifies another approach.

There are many ways to quantify operational problems so that new technology, if applicable, may be applied in a rational manner. For example, "functional tasks" may be quantified in any one of several ways. They may be ranked in terms of impact on mission success or in terms of degree of difficulty or complexity. In this approach, all tasks must be evaluated for the ranking to have meaning. This becomes difficult when working in a projected future rather than the the experienced present. Pilots can, at least collectively, provide a reasonably complete description of their tasks <2> required for today's operational environment. One element of uncertainty however is, as stated above, the requirement to enumeration of all tasks. Many tasks performed by humans are relegated to the subconscious, moved there in most cases through years of specialized training and not always readily brought to the conscious mind. Tasks performed consciously, however, can usually be defined adequately under careful guidance by experts. In fact, successful elicitation of all tasks is the key to building expert systems in the AI domain.

Next, some technique is needed to establish weightings or importance values for each task. This is very difficult, as task interrelations are inherently nonlinear; however, there is strong motivation to treat them as linear. Such treatment tends to distort the relative merits of all other tasks by forcing them to be relatively equal or in two relatively equal groups (i.e., more or less important or difficult). Another difficulty is in selecting the individual or group to assign weighting values. A single individual will tend to introduce natural biases. Group values must be aggregated through some form of averaging or consensus techniques such as Delphi. In any case, the inherent nonlinearity is suppressed and a true value analysis can be severely degraded.

Operational tasks are, at the lowest level, singularly difficult to grasp and evaluate. Their necessity, difficulty, frequency of occurrence, and significance to mission success vary over all types and instances of missions. To illustrate this point, tasks in a mission might be represented as shown in Figure 1 where they are illustrated as weirs in the 'flow' of mission events. This analogy follows from the fact that all tasks have inherent difficulties and, thus, are potential barriers to success. The net result, as in this illustration, is that while mission success is a function of all the tasks it is, most importantly, not limited by the single most restrictive task. In this analogy, removing a single restriction, even the most restrictive -- tantamount to optimal performance of that task -- has only some limited effect on overall results. Consider that if the tasks are all of

<2>. From their perspective -- heavily biased by training.

tuning, and extensive documentation -- all under tight configuration control. In a system such as the Pilot's Associate, where not only the system's effectiveness but its very survival, including that of the pilot, may hang on the smallest detail, it would be the sheerest folly to incorporate a piece of software before its reliability and overall adequacy have been rigorously established. One important effect of the Pilot's Associate Program will be to accelerate development of operationally useful software in both AI and general data/information processing. This will, in turn, press development of associated programming tools and other aids.

For these reasons, processing technology is of primary concern to the Pilot's Associate program, and furthermore this is the only area in which major breakthroughs and significant improvements are both critical and probable. Sensor and weapon technology, already well in advance of processing technology, is increasing steadily; and improved reliability, durability, reduced weight and increased performance and power are ongoing objectives for airframe and engine development. The successful application of AI in the field of air combat will involve data and information processing capabilities that are far beyond anything currently available, especially in an airworthy configuration.

Development of miniaturization and VLSI circuitry has already progressed to the point where there are no effective limits on the amount of potential computing capacity that can be packaged for airborne systems. The hardware problems engendered by this explosion of demand for data/information processing capability, while they can scarcely be considered solved, are thus showing some signs of tractability.

But, as advanced as classical von Neumann machines will become, the demand for parallel processing to further increase processing speed will drive that part of the Technology Base to its limits.

Software, though, is another matter. It is here that the real challenge lies for research during the next decade and, in particular, in support of the Pilot's Associate Program.

The thrust of the Pilot's Associate Program will be two-pronged. It will take maximum advantage of hardware developed under the DARPA's Strategic Computing Program, and it will create additional demands for the development of new and more advanced hardware and software, providing incentives and stimulus for research at the highest level.

2.2 PROBLEM ANALYSIS

The most common and accepted approach to solving the problem addressed by the Pilot's Associate Program is to establish mission requirements and from these define mission functions. The next step is to decompose those functions into tasks, and those tasks into subtasks etc. until a manageable level of task description is achieved. At this point tasks are evaluated in many ways. First, tasks analyses can be performed to identify those inhibiting successful execution of the function. Limitations may be purely technological or human, or both. In the case of technology limits, new technology programs are instituted

destroys you, or causing the threat to be ineffective through ECM against the platform, the weapon, or both.

Avoiding a threat is not always consistent with completing mission objectives. ECM cannot always be relied on, and all other options require precise knowledge of the platform and/or weapon type, its lethality and its state vectors. If evading is the selected option, then precision requirements on the threat weapon state vectors are significantly increased, as timing to a fraction of a second is required for evasive maneuvers for some weapons. Evading a threat is the most taxing choice for survival in terms of external world knowledge because of state vector precision requirements. As in the two previous approaches, complete and accurate information on the immediate external world is paramount for survival.

2.1.2 Technological Issues

Inherent in today's mature technology is a significant improvement in the operational effectiveness of our airborne weapon systems. Sensor technology will be able to provide data on objects within the battle space of the airplane; computer hardware and processing technology, given sufficient impetus will be able to process data into information including tactical and mission options; and communication technology will permit rapid unambiguous dialogue between the pilot and the system at relatively high symbolic levels. Most of the sensor and communication technology is receiving focus through various service programs. The critical areas are data and information processing including hardware and software, but most critically the processes themselves.

One might ask why such problems exist today in light of the current level of technology available. In answer, for mostly economic reasons, much of today's mature technology in many fields is not resident in current operational systems. Only ECM and related technology has the force of need to be reasonably up-to-date on operational aircraft. But the premise is correct, current technologies, especially computer microprocessor hardware, could permit a significant increase in information processing capability and associated increases in option generation and decision making. And much of this technology will find its way into the coming generation of new airplanes. But the pace of growth in environment complexity will cause the problem to outstrip even current "advanced" technology's ability to solve it. And the problem will not be easy to resolve for, unfortunately, there is a direct relationship between combat intensity and the need to make more and more complex decisions. It is not possible to relegate hard real time decisions to periods of low workload - nor is it possible to limit decisions to simple ones during periods of high stress and time compression. These are the technological problems at issue in the development of a Pilot's Associate.

There is a vast difference between operational software and software used as a research tool, whether in AI, data processing in general, or almost any other software area. Before it becomes operational, a program or algorithm must go through an extensive and time-consuming process of testing, correcting, improving and fine

On such an initial WPN strike, NATO forces defending against massive raids must be capable of operating in either a cooperative or in a highly autonomous mode and without VID capability (i.e., BVR in this case can be beyond arm's length). Because of our numerical inferiority, fratricide is not acceptable, but neither is permitting a successful enemy mission. NATO forces must be capable of dealing with a dense ECM environment and low-altitude, silent raids, or both, in many different sectors simultaneously. In any case, finding and identifying targets and getting within lethal range of a significant number of strike aircraft before they release their weapons is a major requirement. Similar issues are associated with friendly strike missions, both CAS/BAI and DI.

Effective Weapon Employment

The problem of achieving effective weapon employment starts with the pilot knowing the enemy's location and whether or not he can be brought within lethal weapon range. In air-to-air engagements, this requires that the target's state vectors be known with some degree of precision. In addition, confidence in the weapon's effective lethality may be enhanced if the target can be classified. However, as range to the target closes, both friendly and hostile weapon effectiveness increases, and when in a numerically inferior position leverage against you increases rapidly.

Range is not the only factor governing the ability to employ a weapon effectively. Heading, altitude, target aspect, relative altitude, absolute and relative speed, and line-of-sight rotational rate can be equally important considerations. Thus, being denied detailed state vector, ID, or classification information can significantly inhibit effective weapon use.

Use of certain air-to-surface weapons, particularly unguided devices, demands high-precision delivery. That, in turn, requires specific conditions of approach to the weapon release point. These conditions require concentration, and are not readily achieved under heavy fire, especially from guided weapons. This situation can be further complicated when successful mission completion requires the use of weapons (similar or different) sequentially <1> against different targets during a single pass.

Surviving

Surviving an engagement is dependent on the ability to detect and evaluate (particularly classify) threats early enough to take appropriate action. In most of the envelope about an airplane, threat state vector data are simply not available, let alone with the precision required. In fact, the volume of combat space around a modern airplane covered by precision sensors is roughly 1/150 of the volume of interest. This is the cause of most losses -- the threat is simply never seen. Appropriate action could consist of breaking off the engagement (avoidance), evading a weapon in flight, destroying the threat before it

<1>. Or worse, simultaneously.

The first step in establishing requirements for the Pilot's Associate is to determine the impact each phase will have on system requirements.

Getting Within Lethal Range

Getting to within lethal range of the target is:

Easier

In daylight
At altitude
With navigation aids
With a large fixed target
In a clear rf environment
With air superiority
When lethal range is large

More Difficult

In inclement weather
On the deck
Autonomously
With small, mobile, camouflaged targets
In a jammed environment
Under fire from above and below
When lethal range is constricted

Designing for the optimistic case is not realistic, nor is it feasible to design only for those cases where success is easy to contemplate. It is necessary to look at all mission types and their characteristics and pick the toughest for setting requirements. One of the most difficult and decisive combat arenas will be the opening day(s) of a Central European conflict with the Warsaw Pact Nations (WPN). Forces at the WPN's disposal are significantly greater in number than those of NATO for all types of aircraft. Initially, all supply lines will be full and significant stockpiles of weapons will be ready, but the WPN are opposed by a technically superior force capable of denying them a sizable portion of their initial objectives -- objectives essential to their overall strategy in such a conflict. Therefore, it is not unreasonable to assume they will use every advantage to deny the opportunity to blunt their initiative. As a minimum, they will select both natural and man-made environmental conditions that make NATO pilot's tasks extremely difficult. One can be tempted to minimize the WPN threat based on known deficiencies in system performance, operational doctrine, moral, etc. - but this can be dangerous.

Since their initial targets are well known and essential to their initiative they will be prepared to use all environmental, electronic, and deceptive advantages and related tactics available to them. Therefore, it must be assumed that NATO systems will be required to operate in unfavorable weather, probably at night, against massive numbers of enemy planes (whether or not preceded by CBW), deceptive formations and maneuvers, and electronic countermeasures. Their objective will be to destroy the bombers before they reach their weapon release point. The enemy's defensive objective will be to prevent the NATO forces from getting within lethal range of their bombers. This can be accomplished by intimidation (more easily effected through large numbers), diversion (forcing engagement with escorts rather than pursuit of bombers), by effectively reducing the lethal range of NATO weapons (by denying indispensable target vector and identification information at clear environment ranges), by destroying the NATO fighters and by combinations of all four.

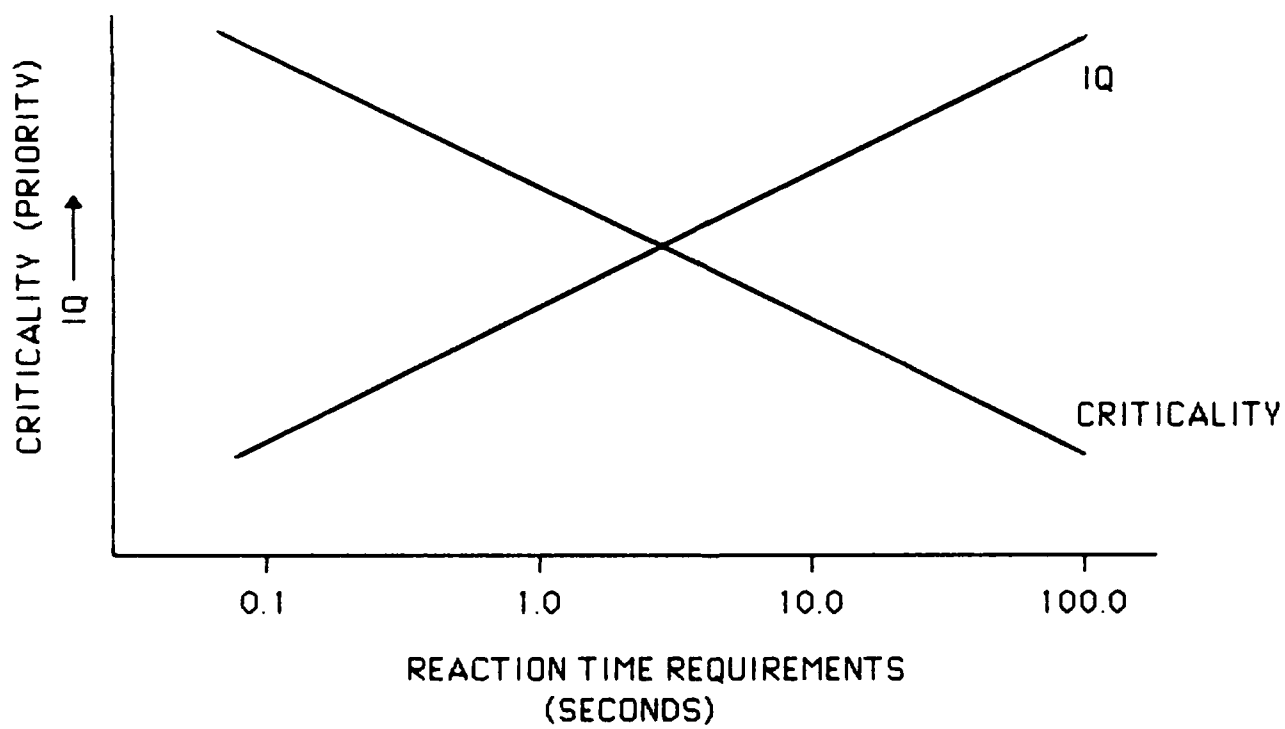


Figure 5 Information Processing Bandwidth Implications

The measure of criticality is intended to imply that if a task must be completed in a very short time, the variance on that time is probably critical. For instance, the detection of an unanticipated obstacle while flying TF/TA requires an almost instant response for survival. There is no time to 'think' about it. An unfortunate but real example is the case of the DC-10 airplane that lost an engine just after leaving O'Hare airport several years ago. Investigations showed the accident probably could have been prevented had the crew been able to comprehend the nature of the problem and act accordingly in the time available. They could not because they were too intelligent to process the situation data with no prior warning, nor had they been trained in how to react to that special set of circumstances. Such training for all possible emergencies is out of the question.

As the useful intelligence of the machine increases, then, the possibility exists for either man or machine to execute a specific process -- neither one 'does it best' but both can do it, with different limitations. In these cases, it will probably be desirable to provide for either, with the human given override authority.

There is one more hierarchy to be considered in understanding the relationships among all elements of a mission and the systems designed to implement them. This is the use of models as a basis for decision making.

Since humans have characteristically made all decisions in air combat, there has been little reason to consider how the human goes about making those decisions. But now that AI is contemplated for combat systems, it is necessary to analyze and evaluate human information processing, to the extent that it is understood, to determine the degree to which it should influence the way we design systems integrating humans and non-human intelligent subsystems.

Three characteristics are worthy of note. First, it is now generally accepted that humans make great use of models of the world of interest about them. Second, apparently many models are used, of varying degrees of complexity and for special purposes. Third, these models are combined in a hierarchical structure such that:

- * information processing is performed in separate information processing modules
- * these modules are defined and linked in a hierarchical structure like that shown in Figure 4 such that data bandwidths are minimized between modules; and
- * the symbolic content (IQ) increases from the bottom to the top of the hierarchy.

SECTION 3

MISSION ANALYSIS

3.1 MISSION SELECTION

Air warfare can be divided into three basic categories, Air-to-Air (AA), Air-to-Ground (AG) or strike, and "other" including ferry, tanking, cargo and personnel transportation, reconnaissance, surveillance and many others. Of these, only air-to-air and air-to-ground involve combat as a primary mission objective, consequently these missions place the highest demand on the cognitive processes of the pilot and crew. In fact, mission elements in "other" can be found in the AA and AG missions, therefore solutions evolved for these missions can be easily translated into their appropriate equivalence in the "other" mission category. Consequently, only AA and AG missions will be considered for applicability of AI and development of a Pilot's Associate.

Air-to-Air missions can involve a large spectrum of types depending on specific objectives and local conditions, however, they tend to fall into one of four basic classifications:

- * Fighter Sweep - This is a patrol mission where fighter aircraft fly a prescribed pattern while attempting to locate enemy aircraft. This mission is used as a routine patrol to "sweep" the skies clear of enemy aircraft to maintain air space control.
- * TARCAP - TARCAP (TARget Combat Air Patrol) is used to maintain airspace control above a target area. It could be in conjunction with a strike (providing cover while the strike forces executed their mission) or a defensive patrol to provide quick response to enemy attack against a critical target.
- * BARCAP - BARCAP (BARRIER Air Combat Patrol) is primarily a defensive action, designed to provide a barrier against penetration of enemy aircraft. Functional requirements of both TARCAP and BARCAP mission are similar, only dimensions of the defended area are different.
- * Defensive Counter-Air (DCA) - This is a general mission title referring to defense of a specific, usually high value, target. It can be initiated either from CAP (similar to the defensive mode of TARCAP) or by scrambling fighters and vectoring them to an intercept point with the enemy raid. This mission is particularly characterized by the need to defend against a large (frequently a regiment size) strike force escorted by a large fighter escort.

Because of the numbers involved, and the stressing environment, this is probably the most severe Air-to-Air missions.

Each of these missions has been studied for its applicability to the Pilot's Associate including generation of typical scenarios for each. It has been concluded that Defensive Counter-Air is the best mission choice as an example for development of the Pilot's Associate, and will be discussed further in the following sections.

Air-to-Ground (Strike) missions also involve a broad spectrum of operational conditions depending on target location in relation to the FEBA and the nature of ground and air defenses surrounding the target area. There exist three basic categories of strike missions characterized by ingress and egress requirements and the nature of the target environment. These missions are described as follows:

Close Air Support (CAS) - CAS provides ground target destruction capability in the vicinity of the FEBA in support of ground forces engaged in combat. There are no real ingress or egress requirements, since the engagement takes place at the FEBA. However, there is need for extremely rapid response on the part of the CAS aircraft to suppress enemy action as soon after it commences as possible. Furthermore, the targets assigned are usually determined shortly before the strike is called, minimizing preparation time for the CAS aircraft. The environment requires extremely low altitude operation with the primary threat coming from small weapons and guns rather than sophisticated SAMs. Because of the extremely hazardous nature of this mission, and an anticipated increase in that hazard in the 1990's, more emphasis will be placed on means other than manned aircraft for support.

Battlefield Air Interdiction (BAI) - Direct support of the battle zone at the FEBA is provided from an area up to 50 kilometers behind the lines. In this region replacement and supply resources are marshalled and moved to the FEBA to support the battle. The BAI mission involves penetrating this area and destroying the enemy's ability to replenish his forces. Some ingress and egress is required and more time is usually available for strike planning since time pressures are somewhat less than in CAS. On the other hand, the same time regime permits the enemy to install more sophisticated defensive systems in the vicinity of high value targets.

Deep Interdiction (DI) - Long term support of the battle at the FEBA is provided from marshalling areas and supply depots well behind enemy lines (200 to 300 km). Deep Interdiction requires deep penetration on ingress and egress through extensive and frequently sophisticated enemy defenses. In addition, the target area is usually heavily defended making weapon delivery difficult. Finally, it is more probable that encounters with enemy fighters will occur during ingress and egress on DI than on the other missions.

Deep interdiction has been chosen as the baseline AG mission for the Pilot's Associate development because it presents the most challenging sequence of events with the greatest diversity. Such situations provide the opportunity for the data/information overload conditions which require the Pilot's Associate. It is felt that problem solutions generated by the Pilot's Associate for the deep interdiction mission would most probably be applicable to the other missions thus maximizing the operational return on the development effort. Furthermore, the higher probability of aerial engagement during ingress and egress provides a closer tie to the air-to-air missions, permitting the greatest interchange of Pilot's Associate technology.

The remainder of this section presents detailed material about the selected Air-to-Air and Air-to-Ground missions including detailed mission descriptions, sample time lines, and a preliminary analysis of pilot workload and task criticality. Representative scenarios are used to examine work loading problems. It is noted that work load can be dependent on scenario specifics, however, reasonable care in the selection of scenarios for analysis throughout the program will provide a sufficiently general basis for development of the Pilot's Associate.

Many sources of mission and scenario descriptions were examined during the course of this study including previous man-in-the-loop studies, studies sponsored by the Air Force and Navy in related areas, and descriptions of 1995 missions and scenarios generated by various intelligence agencies (References 1-7,11,12,14,16,19,21-24). Additionally, many operational fighter pilots were interviewed to gain their perspective on the particulars of this study (References 9 and 20). This review focused on identifying those areas where AI and other Pilot Associate technology can best be put to use.

Appendices B and C present details of air-to-air and air-to-ground missions as supporting information about general applicability of the Pilot's Associate even though the DCA and DI missions were selected for baseline scenarios. Information presented is preliminary; however, and more complete representations must be developed during the Pilot's Associate program to insure broad applicability of the concepts to all missions.

3.1.1 Defensive Counter-Air (DCA) Mission

Essential requirements of the DCA mission are rapid response from an "alert" condition and intercept of a large group of penetrators. This scenario involves interception of a large number of aircraft at very low altitude. Makeup of the target group consists of three types of aircraft -- fighters, bombers, and jammers. The interceptor's primary mission is to stop the bombers from reaching their assigned targets. It is assumed that the interceptors are initially on the ground at air bases serving as the primary strike group targets. The scenario is centered about a U.S. base or group of bases such as those at Bitberg and Hahn in West Germany. Raiders are divided into three groups of roughly 18 aircraft each, with a mixture of the three types of aircraft in each group, e.g., four fighter escorts, two escort jammers, and 12 bombers.

Initial raid detection will be made by the early warning system NADGE, deployed to provide coverage across the FEBA. Detection is passed to the central communication center who makes the attack response decision. Ultimately, six fighters from each of three bases under attack will be scrambled to intercept the penetrating raiders. It is at this point that the mission formally begins. Interceptors will fly out in pairs to engage the invaders. The plan calls for two of the six fighters in each group to engage the escorts, with the other four fighters holding back to attack the bombers.

Figure 6 depicts a top-level pictorial representation of the defensive counter-air mission. The interceptors fly out on a lead collision course at altitude 1.5 Kilometers and a speed of Mach 0.8, with vectoring provided by GCI. The objective will be to intercept and engage the raiders before they split and head for their respective targets. The raiding force is expected to remain intact until it penetrates the heavy defenses of the forward area, counting on its large numbers to minimize attrition.

After the scramble is accomplished and the interceptors are airborne and headed towards the penetrating group, the next step is detection of the raiders. Accomplishment of this task may be adversely affected by the heavy jamming postulated in this scenario. Resulting degradation of sensor performance has the effect of compressing the time scale of all subsequent events in this mission. At some point (radar burn-through at the latest), detection will occur and the air combat system will have to make an initial tactical assessment. Based on results of the assessment, some course changes may be necessary. Acquisition and target track file set-up will follow as the sensor signals settle down. Ownship sensor information will be integrated and combined with information from other sources to form track files. With the track files in place, formal target ID and raid assessment can begin. This will be important in determining particular target packages to be attacked by particular interceptors. ID will be important in separating any friendly activity nearby or potentially intermixed with the raiding force. Once ID is accomplished, a determination of the number of enemy aircraft in the attacking force is required before the final decisions on target priorities and assignments can be made. All of this provides information to the air combat system to be used in tactical assessment.

The raiding force is assumed to remain in formation until it receives warning of the attacking interceptors. At this point, the jammers join the escorts and accelerate to engage the interceptors.

As the mission continues, the interceptors will proceed to formulate battle plans. These plans will include maneuvering to achieve a desired intercept geometry, developing an attack sequence, establishing optimum firing times, and making breakaway contingency plans. Coordination with other NATO assets is a critical element in the battle planning to ensure the maximum use of the total assets. However, for purposes of this study, the rest of the scenario will be described from the viewpoint of a single defending aircraft, with the understanding that it is not alone in its mission.

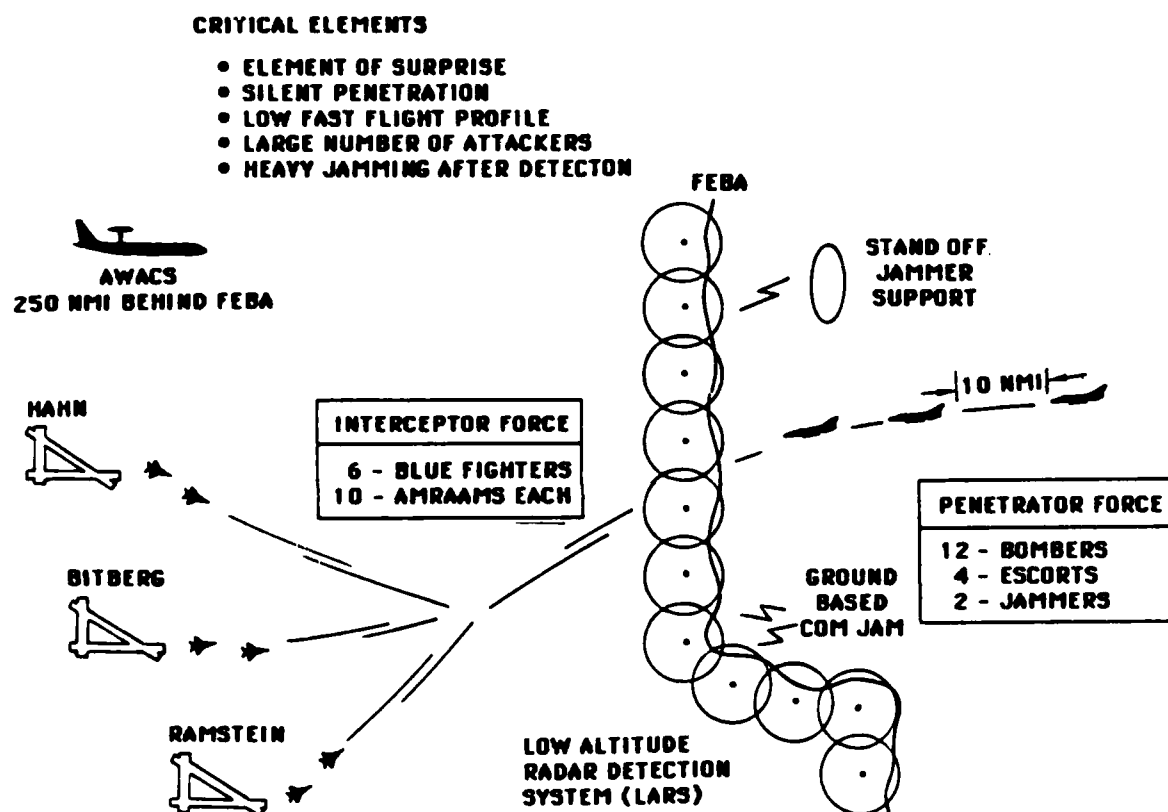


Figure 6 Defensive Counter-Air Functional Flow

The battle plan will evolve as the mission evolves. Flexibility and unpredictability will be crucial in determining effectiveness. The basic unit for air-to-air combat that evolves in this scenario consists of two friendly aircraft (wingmen) against the responding escorts. From the point of view of the NATO interceptor, this probably results in something on the order of a 1-vs-3 engagement. The remaining interceptors assigned to engage the bombers fall back several kilometers to avoid the escort battle, reduce their altitude, and prepare for a look-down, shoot-down attack on the bombers from an altitude of approximately 300 Km.

Both NATO and Warsaw Pact Nations (WPN) fighters will launch missiles BVR, with NATO postulated to have a first-shot advantage. The decision of when to fire the first missile will have a strong impact on the ultimate outcome of the engagement. Part of the information required for deciding when to launch the first missile will be the predicted enemy tactics -- involving both dynamics and weapons employment. After the launch, if the missile is semi-active, the next critical decision is how long it must be supported by illumination from the NATO fighter. When support is no longer required, the NATO fighter can break off the attack and still have a reasonable chance of achieving a kill. Depending on the assumed WPN capability, he may still be beyond the maximum range of the WPN weapons. As a minimum, the autonomous takeover range for the NATO missiles should provide an advantage over some WPN weapons that are postulated to require longer illumination. If the NATO fighter chooses not to break off, kill assessment and a re-attack decision will follow shortly. A shoot-look-shoot sequence will rarely be possible for the NATO fighter without entry into the WPN launch zone, and this must be weighed with other factors in making the critical decisions. These other factors include the location of other unfriendlies and the threat they represent to the interceptor.

The BVR battle may degenerate into a within-visual-range battle if enough assets survive on both sides and natural environment permits, though the probability of this is low. The relatively close ranges encountered here change the requirements on the air combat system. Suddenly much of the battle is fought with the head "out of the cockpit". This means that the pilot may not have the opportunity to look down at his displays and controls and may instead have to fly and fight by trained response. Launch opportunities in this environment are often quite fleeting, and reaction time is critical to the success of a shot. Many shots are taken in boresight mode currently (References 6,7,8,9 and 20) because it is not possible to get the radar to lock on within the time span of a launch opportunity.

Cooperation and communication with a wingman are essential to survival in the close air combat arena because it is not physically possible to see all the combatants at one time, and clearly two sets of eyes are better than one. A wingman can engage an enemy fighter who has an advantage over a friendly or simply warn another fighter of an enemy presence. Once again, it should be noted that most downed aircraft are killed by opponents that they never detected or perceived as a threat. The key to winning in the close air combat arena is knowing where the enemy is and outmaneuvering him to obtain a shot. Outmaneuvering requires not simply better equipment and execution but out-thinking the

opponent, predicting his actions and reactions, and placing one's own aircraft in a position to take advantage of any opportunity.

For those fighters that engage the bombers, the fight tactics will be quite different. The critical necessity will be to maximize the effectiveness of each shot. Previous multiple-target tests (References 6 and 7) have demonstrated that pilots tend to fly into quite close range against the bombers if they know the escorts have been dealt with. Short-range IR missiles have been the preferred weapon when available, with the longer-range missiles being saved for use against fighters. Situation awareness is critical in this case, where engagement times stretch out while ranges close in. The longer a fighter is flying a predictable path, the more vulnerable it is to attack from enemy elements. Some bombers may have some form of self-protection, which dictates that the fighter stay out of the range and angular capability of the weapon. A fine line must be drawn between holding fire long enough to get a better intercept and firing early enough to keep the bombers from reaching their targets while minimizing the exposure of the interceptors.

Resource management will be an important task in either form of battle. Each interceptor carries a limited payload of roughly 6-8 missiles, assuming there are no shortages of materiel. The supply of weapons may determine the duration of an engagement for an individual combatant -- running out of missiles means that a fighter must exit the arena, exposing both himself and his wingmates. At the same time, there is no reward for being shot down with ordnance still on board. Judicious use must be made of the rather precious assets that are available, as shortages of missiles are postulated for the foreseeable future.

The mission ends for an individual interceptor in one of the following manners: all the WPN aircraft are killed, the WPN bombers break off their attack, the NATO fighter is shot down or damaged enough to inhibit fighting, or the NATO fighter runs out of ordnance or fuel.

3.1.2 Deep Strike Mission

The basic goal of the deep strike mission is the destruction of a fixed target such as an airfield, dam, or factory up to 350 Km behind the enemy lines. The deep strike will classically be conducted with a large force of friendly aircraft, including the strike aircraft, jammers, and escort fighters. This section will focus on a detailed examination of the role and tasks associated with the strike (or attack) aircraft. Much of the information regarding particular tasks came from discussions with operational attack pilots (Reference 20) held in December 1984.

Figure 7 represents a bird's-eye view of a typical strike mission. Distinguishable phases include the takeoff and subsequent transit to the FEBA region, the penetration of the FEBA, the ingress towards the designated target, the attack phase itself, the egress back across the FEBA and the recovery. In nearly any phase of the mission, the strike group might expect to be intercepted by enemy fighters intent on

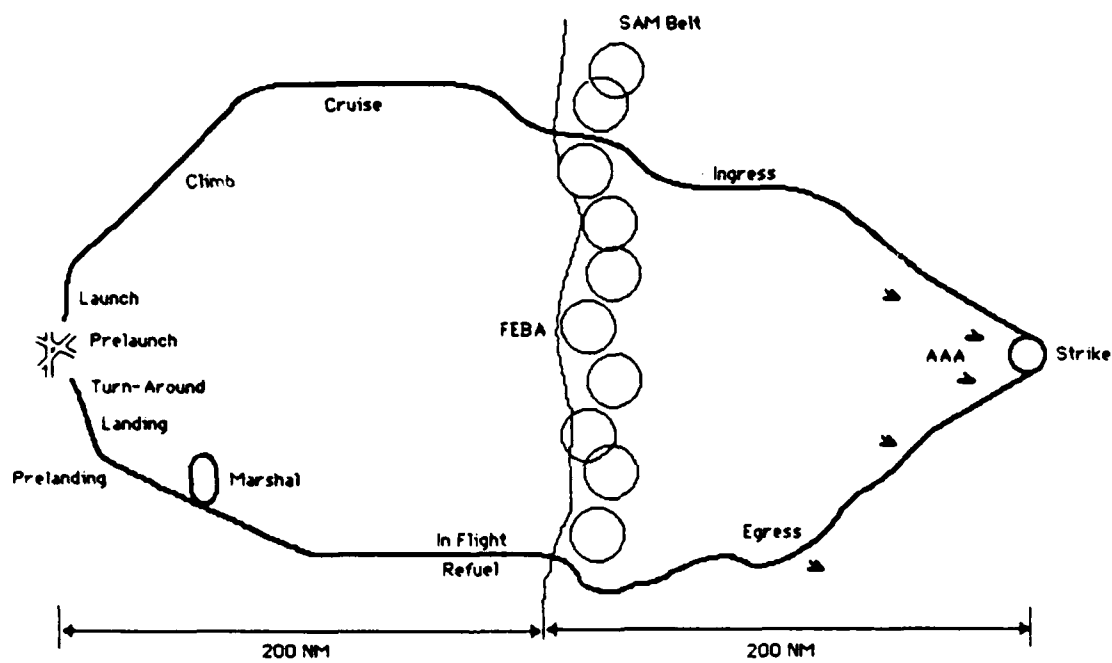


Figure 7 Typical Strike Mission

destroying the group or forcing them to scrub the mission. Interception by the enemy is a near certainty at some point after crossing the FEBA.

The mission begins with a preflight briefing. This is more critical here than in air-to-air engagements because of the more formal character of the mission. Included in the briefing will be weather and intelligence information. Expected enemy defenses, ingress and egress routes, operating frequencies, and generic tactics will also be discussed. Takeoff and transit to the region of the FEBA are not particularly demanding phases. At this time, rendezvous with other elements of the strike force will be made, formations entered, communications, sensors and other equipment checked out, and intelligence updates received. While all of these tasks are critical to the ultimate success of the mission, none of them is particularly difficult or demanding.

The first demanding portion of the mission will be FEBA penetration. Flight profile through the SAM barrier will be predefined. Basic choices will be either low, to avoid detection and slip underneath the coverage of some of the SAM's, or alternatively high, to fly above the coverage of the majority. Both flight profiles have merit in certain situations and scenarios, and will result in somewhat different timeliness. For the low, silent penetration, the key tasks will be maintaining formation while at low altitude and sensing SAM sites while at sufficient range to react adequately. Timeliness will be quite short in this phase, as the line-of-sight to the SAM sites will tend to hinder early detection. A good deal of maneuvering may be desirable as various sites are bypassed or as their sensors lock on to the strike group. Reaction times to the SAMs will be measured in seconds, with the countermeasures employed against launched missiles being the most time constraining. All scenarios examined show the SAM belt as extremely dense, so that in all likelihood the force will be within the launch zone of more than one site at a time. Once detected, the strike force response will be heavy use of electronic countermeasures, with chaff and flares used as launches are detected and missiles are approaching (Reference 20). Maintenance of the strike formation, along with the lower maneuverability associated with heavy ordnance loads, may limit the ability of individual aircraft to avoid SAM missiles.

For the high-altitude penetration profile, reaction times will generally be larger, due to increased distance between the ground-based threats and the strike force. However, there will be no question regarding enemy detection of the raid, so jamming will be used throughout. Patterned flights such as weaves may be used to confuse SAM fire control systems and to provide more situation awareness by effectively increasing the sensor volume coverage.

After penetration of the FEBA SAM belt, the raiding force will reform as necessary and fly a preprogrammed path towards the target area. The region from the FEBA to the target area can be expected to be relatively lightly defended by SAMs and AAA and the programmed path will be designed to avoid the known defense positions to the largest extent possible. However, it is in this region that interception by enemy fighters is most likely to occur. Air surveillance by the strike force at this time is a critical, although not a time-demanding task.

Communications with other strike members will be necessary to coordinate sensor coverage and to maintain situation awareness. When target contacts are made, time-critical decisions must be made on how to proceed, both for the strike force as a whole and for the individual components. The same series of events as for the air-to-air mission must occur to provide the necessary information on which to base decisions, including formation of track files, target ID, raid assessment, and the formation of a battle plan. Roughly the same times are available for each of these tasks if detections occur at a satisfactory range (e.g., greater than 75 Km). As the initial detection range decreases, time available for each task is compressed and, as discussed earlier, the chance of a less-than-optimum decision becomes higher. The strike aircraft is largely dependent on the escorts for protection other than countermeasures such as jamming or chaff and flares.

Events associated with the actual attack phase will be quite dependent on the target complex and the ordnance being carried, as well as on the weather and other environmental factors. Different combinations of the above factors will dictate different approach geometries, speeds, and tactics. Weather may limit the use of certain weapons which had been planned, and the ability for reactive re-planning may be crucial to mission success. The attack phase is of the order of five minutes in duration, with single-pass kills strongly desired. Therefore, timeliness of any required re-planning becomes critical.

As noted, targets and ordnance will largely dictate tactics and thereby the air combat system requirements. Two attack segments were selected to illustrate the potential differences. Selected mission segments differ in weaponry, weapon support requirements, and targets. The first is a night radar/FLIR delivery of unguided bombs on a heavily defended thermal power plant. Figure 8 depicts the basic situation. A low-altitude, high-speed route was selected to minimize the threat of command-guided SAMs that are defending the target area. The weather allows for use of the FLIR and demands that the pilot maintain a good cross check of his flight data.

The scenario begins with the flight on a NE heading west of a small mountain range. Utilizing the terrain-avoidance mode of the radar, the flight proceeds through the mountain pass and upon breaking out on the other side, switches to radar map mode and stabilizes the radar on the target area. The air combat system obtains successively finer resolution on the target through the use of the appropriate higher-resolution modes of the sensors. This is a critical part of the mission that is not particularly time constraining, given successful target acquisition. However, if the target acquisition is delayed for whatever reason, this function could become much more critical and difficult as the pressing need for target information increases.

Throughout the run the pilot is warned of SAM radar activity. Whether the aircraft is fired at or not is scenario dependent (not included in this scenario at this point). But the need to sense and react to the SAMs is nonetheless critical to survival and successful weapon delivery. During the final run-in on the target, the aircraft receives heavy AAA fire from about two Kilometers before the target to

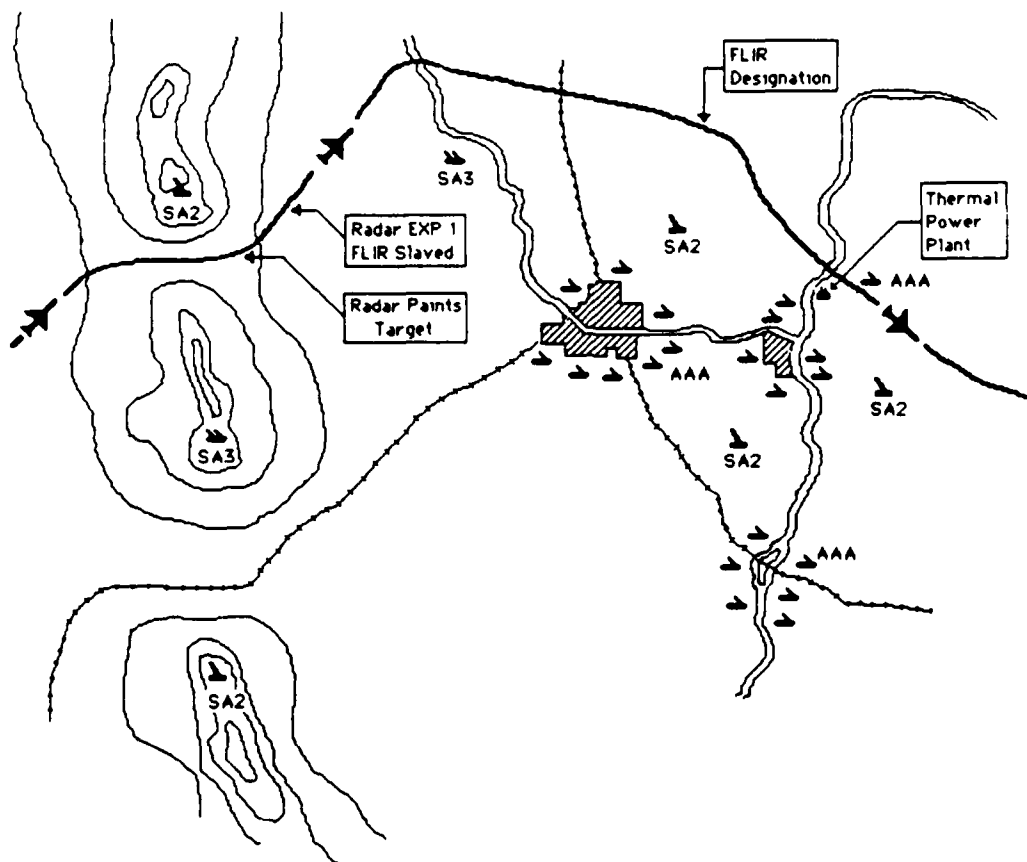


Figure 8 Power Plant Night Attack

about two Kilometers past the drop zone. The most time-critical tasks occur as the bombs are dropped. The unguided nature of the bombs forces the aircraft to be rather limited in their evasive maneuvers, at least immediately preceding and during the drop. During this time interval, constant vigilance is paid to the EW warning sets, which are alive with warnings from the heavy concentration of AAA sites. Automatic weapon delivery systems that free the pilot from flying the aircraft during the actual weapon drop help the overload problem somewhat. However, the real problems are the potentially conflicting demands that weapon drop and survival place on the system and deciding which demands must take precedence in real time.

The second scenario segment as shown in Figure 9 involves delivery of Walleye-type weapons against a railroad bridge. The high-altitude 35 Km stand-off delivery was chosen because of the types of SAMs and AAA utilized to defend the bridge. The weather assumed in this scenario allows this type of delivery. The scenario begins with the flight 45 Km SW of the target, heading north. During this period, the Walleye is preflighted and the bridge is detected on radar and a designation performed. The flight turns toward the target and the Walleye is locked on the target area. After lock-on is verified, the Walleye is launched as the aircraft approaches the 40 Km mark to the target. The Walleye display is monitored and in-flight corrections are made until the pilot is assured of its success. The aircraft then makes a 170 degree turn away from the target and begins egress.

This scenario has a relatively low workload associated with it for a number of reasons. First, the stand-off nature of the weapon utilized allows for launches outside the point-defense range of the bridge defenses. The pilot can employ the aircraft autopilot, which allows him to apply the majority of his attention to the delivery tasks. Lastly, because of the Walleye pod system, the pilot can launch before he can actually see the bridge and then make fine tuning adjustments as the Walleye approaches the target and the aircraft moves away from it. The peak criticality comes as the pilot is adjusting weapon designation. This scenario could be stiffened significantly with the addition of more enemy defenses that preclude an "enemy-free" launch capability, and indeed it can become extremely demanding, as the Walleye guidance fine tuning can be a very precise and exacting job (Reference 21). Similarly, weather may constrain the launch range capability. Bad enough weather could force a radar-only engagement similar to the previous scenario but with different ordnance.

Upon delivery of the ordnance, the strike force egresses at high speed, with escorts falling into trailing position to screen the strike force from interception. The most critical task in this phase will be survival of the interceptors and evasion of the SAM belt near the FEBA.

For completeness, this mission includes an in-flight refueling. This task is variable in difficulty as a function of meteorological conditions, ranging from straightforward in clear, calm conditions to virtually impossible in adverse weather. In any case, refueling requires that the strike group first rendezvous with the tanker at the pre-planned coordinates and time. Exact close formation must be held during the refueling operation with appropriate communications

advantage of it. At the same time, the enemy is trying to do exactly the same thing. Incorrect tactics will often lead to getting killed or at least negating a technical or positional advantage the Blue fighter may have. Specific tasks that require relatively high levels of prediction include determining optimal response to an inbound missile, predicting enemy motion, predicting results of actions against SAM threats, and determining the optimal time to take the selected action.

Another major factor that determines difficulty is the number of possible alternatives that exist. Presumably, not all alternatives have the same potential and will yield different results if followed. Having to choose between a large list of alternatives becomes increasingly important as the time available to sort through the alternatives is compressed. The human can only evaluate alternatives at a relatively fixed pace for a given complexity of problem and alternatives. Not all alternatives will require the same amount of consideration as some may be easily eliminated. However, there are some tasks where there are many reasonable alternatives, some of which offer more utility than others. It is these tasks where the pure volume of alternatives may mean an optimum (or better) choice may be missed due to time constraints. Further, the pure volume of choices may lead to an overall confusion on the part of the decision maker regardless of how much time is available to make the choice (a data overload situation). Tasks where alternatives abound include maneuver selection during a dogfight, the determination of BVR engagement tactics, predicting target motion, action selection against a threatening SAM, and determining new flight path plans to avoid SAM or other threats.

With all the factors that influence difficulty in mind, each of the tasks described in the timeliness of Section 3.2 were examined with the goal of roughly ranking the relative difficulty. Extensive use was made of pilot input (References 9 and 20), hours of man-in-the-loop test observations (References 6,7,8 and 10) as well as the results of previous studies where workload was analyzed. In no particular order, those tasks determined to be most difficult were:

- Correlate all available sensor data (ownship, ground, JTIDS, etc.)
- Detect/acquire/recognize the target aircraft(s)
- Determine air-to-air engagement tactics
- Determine optimum launch range/conditions
- Predict enemy aircraft motion/tactics
- Anticipate/avoid adversary's incoming missiles
- Dogfight/close air combat
- Modify pre-planned flight path/parameters
- Detect and identify SAM threats
- Determine course of action against SAMs
- Unguided weapon delivery in high threat density
- TF/TA
- Required communications when busy with other tasks

3.3.2 Task Criticality

Task difficulty alone does not mean the air combat system should have upgrading in that area. Given limited resources to invest in improving the air combat system, the criticality of tasks to mission

Without proper analysis, it is quite possible to find oneself in a position where a function is not desired but cannot be controlled because it is automated. For example, consider the hypothetical situation where, for tactical reasons, silent operation is mandatory. However, certain enemy radiation patterns are discerned and analyzed as extremely hostile by automatic ESM processing equipment. As a pre-programmed emergency response a jamming pod is activated in the mistaken belief self destruction is imminent.

Each of these, singly or in combination, can dramatically affect pilot task difficulty. Taking a step back, each of the above areas can be effected by how much time is available. The discussion in Section 3.2 has attempted to discuss how much time is needed for certain events and tasks for two selected missions. Any air combat system, which includes the pilot, has an information processing capability that has a limited resource capacity. This capacity determines the time required by the system to perform a task. If the information processing requirements imposed by a task exceed this capacity, the system performance on the task will be resource limited. That is, the system's level of performance will be limited by an inability to optimally use all of the data provided and will in all likelihood produce a suboptimal result.

Time constraints on the completion of a task produce resource limited situations in several ways. For example, the amount of information may be too great to sense or perceive in the time available. Alternatively, although the amount of information is perceivable, the mental or computational operations that must be performed are excessive. Also, the information required to perform a task may dynamically change in time frames too short for the system to be able to process the changes.

Any of these situations can make a task more difficult. In reality, the determining issue is the ratio of time required compared to time available to complete the task. The time required variable is a function of the information processing requirements of the task and the capability of the air combat system, while the time available variable is a function of the mission context in which the task is performed. A task may become more "do-able" (less difficult) whenever either part of the equation is improved - either more time is available to do a task or the system capability to do a task is upgraded. It is interesting to note that since time constraints are a function of the ratio, a system can be resource limited to the same degree in tasks requiring different amounts of time to complete, if the available times are also proportionally different.

Another particularly important factor in determining difficulty of a task is the amount of prediction required. The human mind can be quite good at predicting within rather narrow bandwidths. But as the level and amount of prediction increase over a given time frame, the human becomes quickly overloaded and the prediction quality suffers. This is particularly noteworthy given the importance of correct prediction to the outcome of air combat engagements, especially air-to-air engagements. Many of a fighters tactics are based on estimating what the enemy will do and setting oneself in a position to take

exceeds short term memory limits the options will, of necessity, be flawed. Second, if the time between the need to formulate new options is less than the human's ability to formulate a single set, the entire process breaks down - usually catastrophically. Third, if too much time elapses between acquisition of the first and last items required to formulate options (delayed arousal), then performance suffers. While this last item is not strictly an example of workload saturation, degradation in performance under delayed arousal is probably exacerbated under high workload.

Concurrent Task Performance

Pilots frequently must perform several tasks concurrently such as maintaining visual awareness out of the cockpit while monitoring in-cockpit displays. In addition he may be simultaneously in voice contact with a wingman(men) or base. This situation causes conflicting demands on his sensors and supporting short term memory.

Excessive Small Scale Tasks

Operations requiring several small steps can significantly increase pilot workload. In performing these tasks, operators (pilots) are prone to making errors of omission. In addition, such tasks impose a formidable memory burden that can adversely affect performance on other tasks.

Time-line Compression

Since serial encounters are highly time-stressed, there is very little time available to the pilot to exercise judgement and take action. In a typical low level strike mission, the pilot has a host of tasks to complete between target detection and weapon release. If for weather, ECM, or other reasons the time available is cut the task time compression can be immense, for all of the same detail subtasks must be done.

Pilot Physiological Limits

Humans are limited in the rate they can perform manual tasks. This characteristic is referred to here as a motor limit even though portions of this limit has been identified as cognitive. For example, McCaughan's study of performance in a mirror star-tracking task (Reference 25). A pilot typically needs on the order of one-half second to make a simple control adjustment. Consequently, he is incapable of manually controlling an aircraft requiring much more than two manually executed corrections per second. This could be a problem in some of the contemplated advanced helicopters. Where this situation occurs, some form of automation is not just desirable but mandatory.

Indiscriminate Automation

Automation can be a mixed blessing. If introduced without proper regard for prior task analysis, it can produce effects opposite from those desired, i.e., an increase rather than a decrease in workload.

flight corrections for the Walleye. This is a critical and exacting task that requiring concentrate pilot attention. Other tasks impinging at this time, such as threat warnings, will severely degrade accuracy of Walleye and thus directly reduce mission effectiveness.

3.3 DIFFICULTY AND IMPORTANCE OF TASKS

Here we first develop criteria for assessing difficulty in terms of pilot workload. Then we apply these along with assessments of importance to isolate potential candidates for AI application. <5>

3.3.1 Pilot Workload Factors

Independent and related studies over the past many years have identified at least seven reasons for unmanageable pilot workload. These include:

- 1) Perceptual saturation
- 2) Pilot cognitive time-bandwidth limits
- 3) Need to perform tasks concurrently
- 4) Excessive small scale, routine operations
- 5) Time-line compression
- 6) Pilot physiological limitations
- 7) Indiscriminate automation

Each of these is discussed in the following paragraphs.

Perceptual Saturation

This phenomenon manifests itself when a number of critical events occur simultaneously, with the result that the pilot is unable to cope with the situation. For example, when several SAM's are launched at your ship and are in flight at the same time, the serial processing pilot easily loses track of the threats and control over his reactions.

Pilot Cognitive Time-Bandwidth Limits

Humans have a finite and relatively small limit on the number of different symbols that can be retained and correlated in short term memory (STM). When performing tactical missions, formulation of tactical options generally requires considering a number of different but related factors. Three items can cause overload. First, if the number of factors needed for consideration in formulating options

<5>. This is however but one input to determining those areas most appropriate for intelligent information processing.

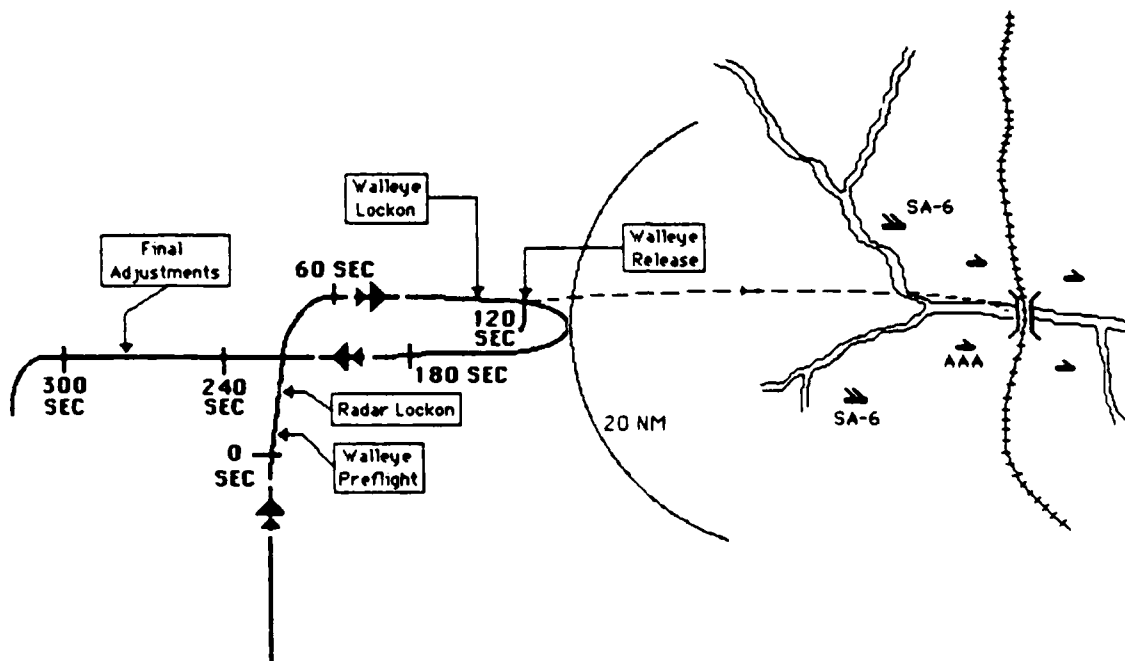


Figure 14 Strike Segment (Walleye)

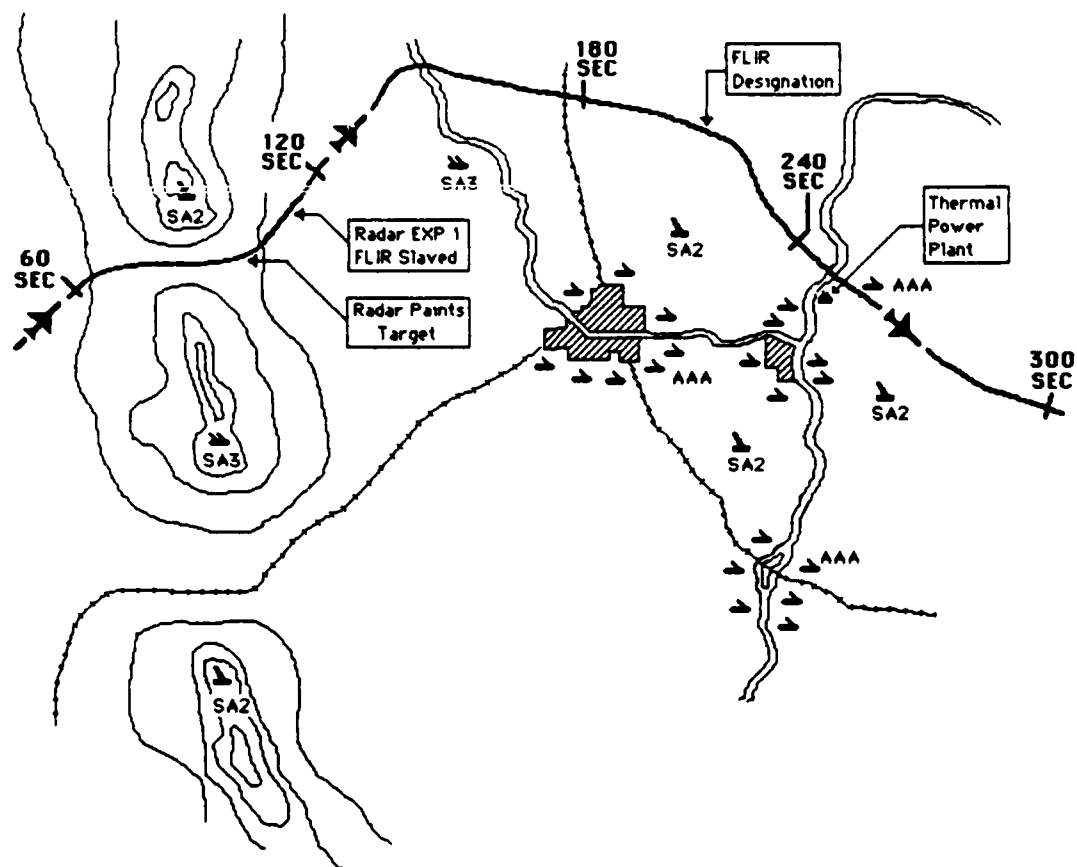


Figure 13 Strike Segment (Radar/FLIR/MK83)

chance of running into an unexpected mobile SAM site. However, these encounters would simply be a subset of the tasks required for the FEBA penetration. However, it is in this lightly defended region that intercept by fighters is most likely to occur. The ensuing air battle has similar traits to the air battle of the defensive counter-air mission and will not be repeated here. Suffice it to say the most time critical tasks in this phase will be timely detection and identification of air threats to the strike force. During the ingress, a programmed flight path designed to ease the trip towards the target will be followed. Key tasks will be monitoring of the threat warning sensors and navigation. The ingress period can last from 15-30 minutes depending on the specifics of the scenario.

Actual target attack ranks with FEBA penetration as the most demanding and time critical mission segment. Most deep strike targets will be heavily defended by SAM and AAA sites. As before (Section 3.1), two specific attack scenarios are considered. Figure 13 depicts the unguided bomb drop mission segment with 60 second time hashes along the flight path. Once the airplane clears the mountain roughly 2 minutes remain to gain proper target detection. This period is used to obtain finer resolution as range closes. During the run-in period, sensor activity from SAMs is quite heavy and launches could be made. Defense alternatives could be limited somewhat by the desired flight path to the target. Basic response times are similar to the low altitude FEBA penetration. FLIR designation occurs at roughly one minute to target.

Actual time over target is quite small, about 20 seconds, and represents the highest workload portion of the mission. Continually checking EW displays for SAM and AAA activity must be interleaved with ordnance delivery. Heavy defense concentration means multiple ESM warnings; these alone are difficult to sort out. The system must evaluate which are most threatening and which demand immediate attention while maneuvering for weapon delivery, potentially at high g. Reaction to the threats, whether jamming, chaff, flares, or maneuvers, often conflicts directly with weapon delivery requirements. Some situations dictate near instantaneous decisions to counter immediate threats. Proper delivery of unguided weapons may so severely limit the maneuvering options of the aircraft that the mission must be scrubbed in the interest of survival. This crucial decision requires integrating a massive set of data in a very short time frame.

After weapon drop, there is a 30 second period where ground-based threats may still engage though now maneuvering options are no longer restricted by bomb delivery requirements. Egress back towards and across the FEBA repeats the same perils and time-lines as the ingress.

The other specific scenario, Figure 14, involves delivery of a stand-off guided weapon such as Walleye. Timely events here will include radar lockon with about a 20 second window in which to achieve lockon and still maintain the desired geometry relative to the target and its defenses. To stay outside the range of the defenses, a launch at 30 Km or beyond is desired. The Walleye achieves lock-on at approximately 37 Km, a critical point in determining mission success as delayed lock-on increases exposure of the strike airplane. After weapon release, the launcher turns away from the target but continues to make

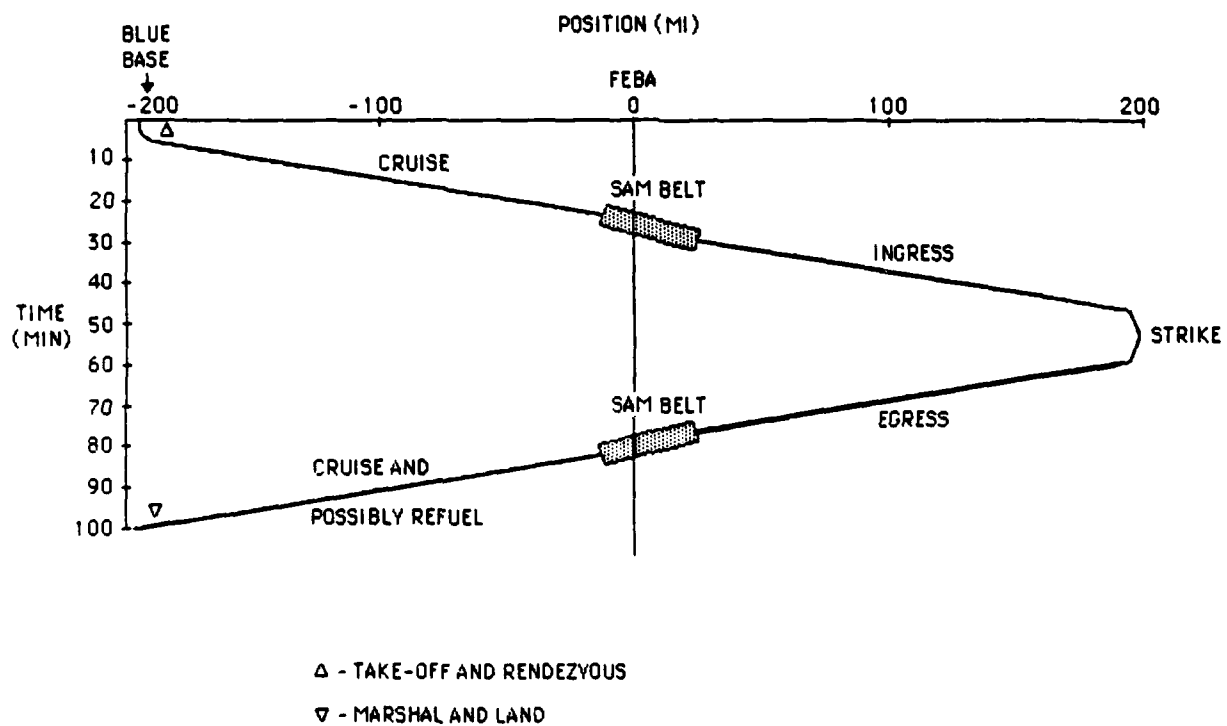


Figure 12 Strike Mission Timeline

first missile, re-attack will generally not begin until after kill assessment. This period allows the target to close another one to three Km. In some cases, the pilot may fire another missile before the first has intercepted. This is done to increase cumulative kill probability, particularly if the target is highly threatening (References 6,7,8,10).

At this point, visual range is quickly being reached. Requirements of close air combat have been discussed at length appendix C.6 and will not be repeated here. Suffice it to say that the keys to success in close air combat are knowing where all the potential threats are and out-maneuvering the opposition to gain a shooting advantage.

3.2.2 Mission Time-line for Deep Strike

Deep strike missions differ most dramatically from defensive counter-air missions in featuring more time critical events concerning survival rather than attack. Though air attack is probable during a strike mission, its sequencing is similar to that discussed above and would be dealt with primarily by escorting fighters. Here, times associated with air-to-surface aspects of the mission are focused on.

Figure 12 depicts a typical strike mission including times associated with major phases. The first 20-30 minutes of the mission are not time critical as events generally do not overlap and are by themselves relatively straightforward to accomplish. Tasks include take-off, rendezvous with other strike elements, getting into formation, checkout of communications and other systems, and transiting towards the FEBA on the preprogrammed flight path. The highest workloads occur during periods of communication with other strike elements (wingman, within flight, and between flights). As a general statement, communications often cause disproportionate workload increases and are often the first task bypassed when the situation gets hot (Reference 20).

The first time critical events occur as the FEBA is penetrated. Key tasks include detection of SAMs, building a response plan against threatening SAMs — both for ownship and the flight, and executing the plan. Reaction time available depends on flight profile and proximity of threatening SAMs. Time of flight for SAMs against low altitude strike forces are up to about 20 seconds with added warning time of maybe 10-15 seconds prior to launch gained by detecting SAM radar lock-up (ESM). For IR SAMs, the warning and reaction times are significantly less. For high altitude flight profiles, SAM flight times are upwards of a minute. The most critical task will be the timely execution of the selected response to an inbound SAM missile. Response choices are similar to those for an inbound air-to-air missile and include evasive maneuver, dispensing chaff and/or flares, jamming, and speed changes. Early or late execution of many of these responses can negate the effect of the response and thereby lessen probability of survival. Total time to penetrate the SAM belt is from 3-5 minutes.

Penetration of the FEBA is followed by a relatively quiet period of ingress towards the target. Most scenarios define a lightly defended region from the FEBA to the high value targets located 150-300 Km behind the lines. Some SAM and AAA sites may be encountered as well as the

limited but diverse in consequences. To complicate matters, the signs of trouble are often subtle.

Following take off, three hundred seconds has been allotted during which the raid closes approximately 55 Km. Once airborne and vectored toward the raid, pilots of the interceptors make an initial situation assessment and agree on sensor coverage responsibilities. Each airplane begins radar search, waiting to achieve initial detection of the target group. In a clear (passive target) environment, initial detection ranges of 90-150 Km might be expected after searching 40-50 seconds. Next, 10 seconds were allocated for pilot assessment of reports from several subsequent search frames. Based on such additional reports, the pilot changes course to gain a preferred intercept geometry. This course change requires only crude angle measurements and typically takes up to 7 seconds to execute. Target tracks will be formed as soon as reliable range data are available, depending on radar performance and ECM environment. The actual time to initiate the track is 2 seconds per track (after range information is available).

Concurrent with forming the track file is the beginning of the target ID process. Depending on the quality and variety of the available sensor information, the ID process may take a minute. Target track file and ID data are both used to build a tactical battle plan -- assess the situation, select targets for attack, plan the actual attack and select maneuvers yielding tactically desirable relative geometry and kinematics. This planning mandates close coordination with wingmen throughout. Time available ranges from 5 to 60 seconds depending on target group range, closing rates and target threat level. Battle planning suffers severely from late target acquisitions whether caused by jamming or merely inattention. Battle plan quality goes a long way in determining engagement outcome. A poorly conceived battle plan can negate any firepower advantage a fighter may have. Similarly, a battle plan formulated before complete and correct information is available promises the same result. Time compression leads to poor battle plans by imposing cognitive loadings that exceed human time/bandwidth capacities. By necessity, this forces the pilot to ignore or overlook key information that should affect his planning. Many man-in-the-loop tests (References 6,7,8,10) have revealed this phenomenon. As the situation heats up, pilots say they have a tendency to go into "tunnel vision" on the most critical task at that time (Reference 20). Unfortunately, tasks ignored (or focused on) are neither deterministic nor appropriate to current circumstances.

Once the battle plan is in place, it can take as little as seven seconds to achieve "bird away" and then roughly three seconds between subsequent shots. Attaining knowledge of target state, particularly range, and intent, particularly ID, is crucial for predicting missile effectiveness which determines suitable firing points. Flight times near maximum range are on the order of 50 seconds with approximately 30 seconds of illumination support required.

Kill assessment is next. Time required varies as a function of kill type, quality and variety of sensors and environmental conditions (e.g., day/night, cloud cover). Times assigned to this function range from 5 to 15 seconds. If the pilot has waited until intercept of the

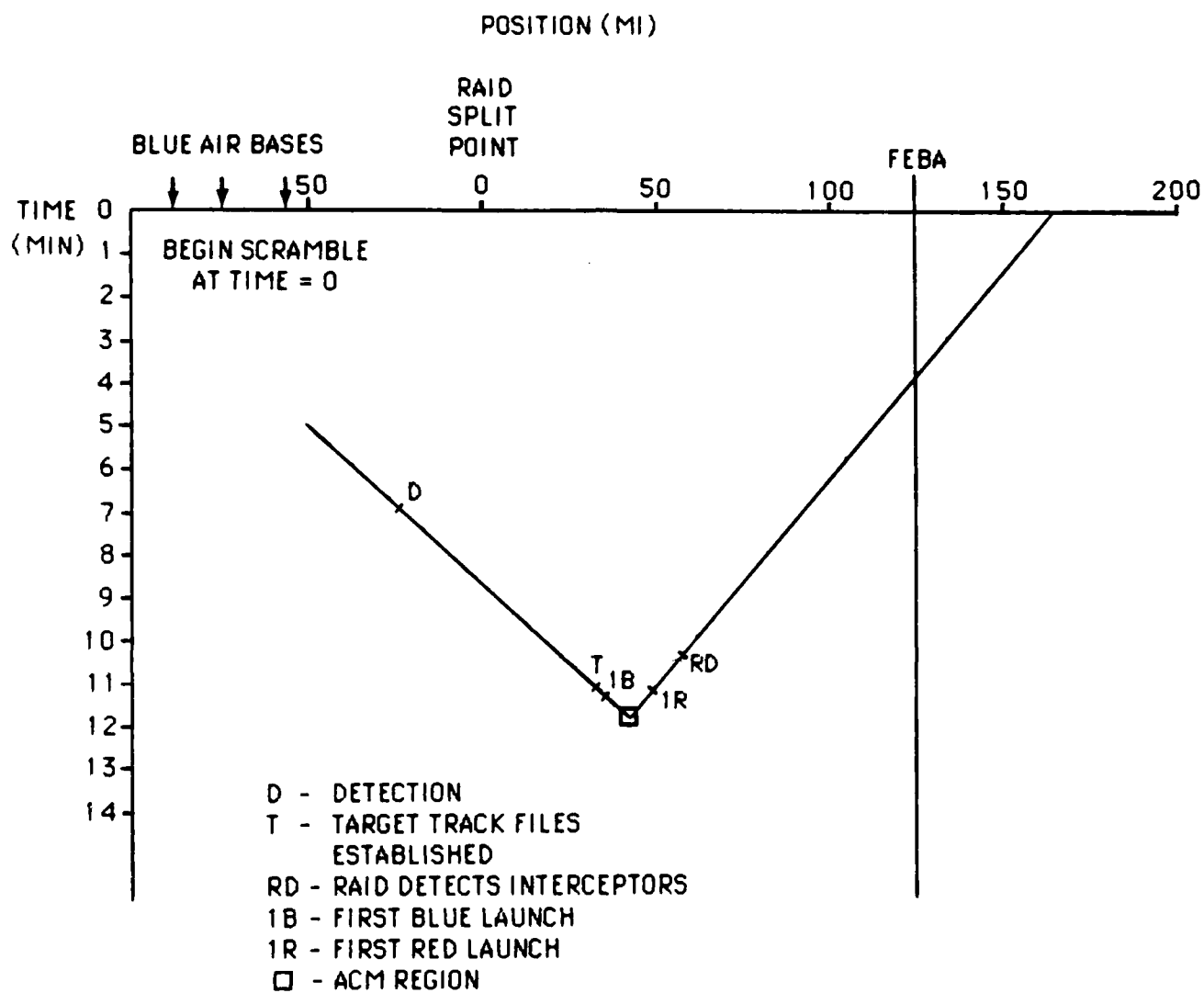


Figure 11 Defensive Counter-Air Timeline (Jammed)

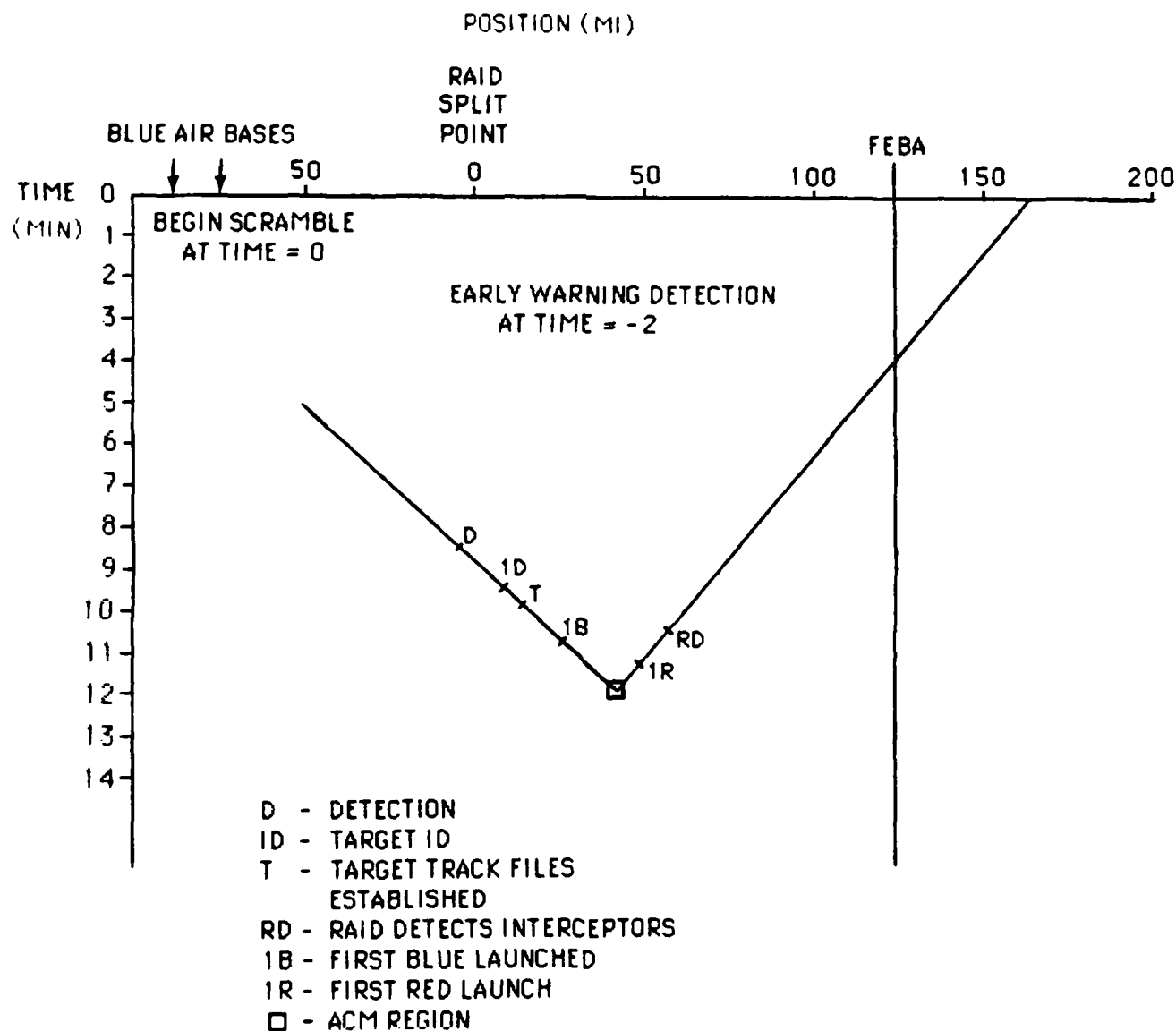


Figure 10 Defensive Counter-Air Timeline (Clear)

maintained. The large amount of time available to accomplish this task (given that fuel is not critically short) eases the difficulty, and with proper training, refueling becomes a relatively routine task.

The mission ends with recovery at the airfield.

3.2 MISSION TIME-LINES

This section reports on efforts to identify tasks and events critical to mission success and difficult to accomplish. Previous sections have described various missions and some of the requirements on the part of the air combat system to complete the mission. Two missions were selected for more in depth study - defining the mission in more detail as well as identifying tasks and events. This section will look at timeliness, identify critical paths in determining the outcome and try to identify particular bottleneck tasks. Sensitivity of mission success to timing variability will be discussed where significant.

3.2.1 Defensive Counter-Air Mission

Air combat missions are a sequence of events and processes, many of which depend on preceding processes. Within a particular mission and scenario, time limits can be defined. In this section, times are assigned for completion of a given event. Time estimates were based on discussions with experienced pilots (Reference 20) plus review of other recent pilot workload related studies (References 3,4,21, and 22). The intent of this timeline study is not merely to assign times to tasks and then tote them up to see which task groups take the most time. Rather it is to provide insight into task concurrency and where overload likely would start to build.

Figure 10 is an upper level timeline versus range depiction for the defense counter-air mission. As discussed earlier, this mission can feature a variety of electronic environments ranging from clear (and non-radiating target group) to severely jammed. This timeline assumes the former, either a non-radiating target group, a less severe jamming environment or an effective passive ranging technique that allows essentially clear detection performance. On the other hand, Figure 11 assumes badly degraded sensor capability that results in no track file for launch purposes until burnthrough range (assumed 25 Km). These two figures demonstrate jamming's time-compression effect. Degradation of detection range in the second case suffices to reverse first shot advantage from Blue to Red. Reference 4 showed a sensitivity of 2 seconds decrease in available reaction time per 1.5 Km reduction in track initiation range. The clear case gives us data on minimum times to accomplish necessary tasks. Where the jammed case denies that minimum time, help is warranted -- from AI or other sources.

The mission begins with scramble. Takeoff presents the first challenge to the pilot. This critical segment requires the pilot to assess his plane's status to determine if he can lift off safely, or if he must abort. The decision window is very small, and the options

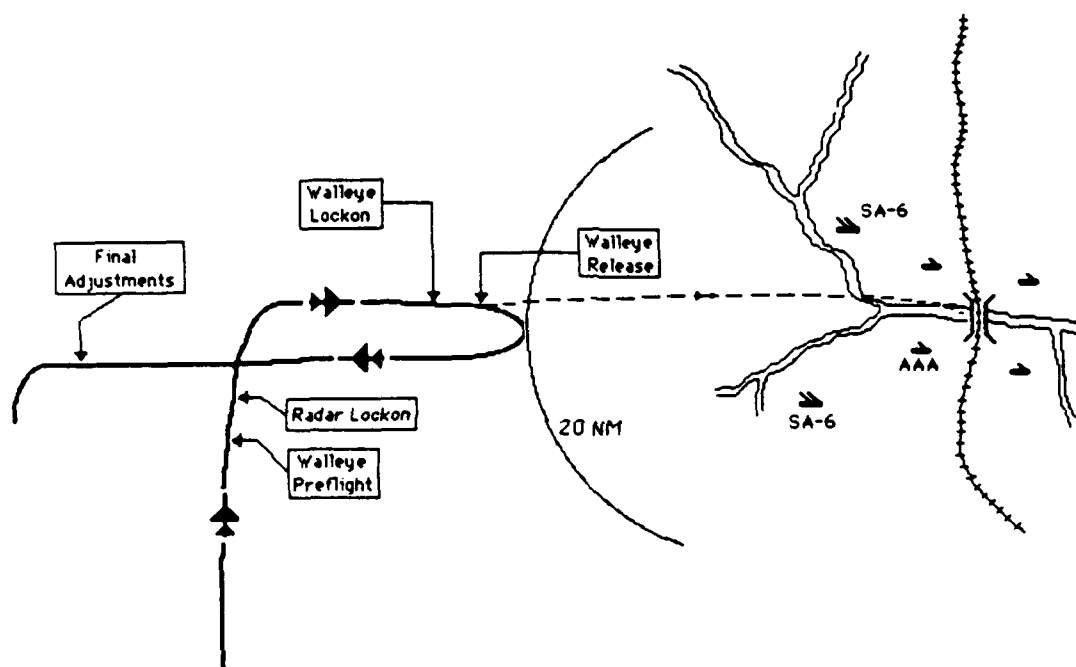


Figure 9 Guided Weapon Attack on Bridge

success must also be considered. It seems logical that those tasks which are most critical and are difficult to achieve be the first examined for possible improvement via artificial intelligence. There are a number of tasks that are critical to mission success that are not particularly difficult, such as take-off. Because it is easily done today with existing systems, take-off probably is not a good spot to invest resources. Other such areas include maintaining target tracks, following flight path plans over non-hostile territory, carrying out a maneuver meant to achieve tactical superiority (once the maneuver is decided upon), and closing on the target when out of zone.

Of greater interest is those tasks which are critical in determining mission success but are not simple to accomplish. Many of these have already been discussed in the context of particular missions. Criticality can be examined from a number of views. One assessment can be the penalty associated with making a wrong or bad or no decision. This may be different from the penalty of making a less than optimum decision or assessment. The first situation may ensure a failed mission while the second may or may not allow a successful completion of a task. This really involves the level of correctness. As an example, consider the task of target identification. If a friendly aircraft is misidentified as a hostile and is shot down, the penalty for this wrong decision is rather severe. Similarly, if a hostile is identified as friendly and it ends up shooting down the Blue aircraft, the penalty of this wrong assessment is severe. However, if a enemy fighter is misidentified as a MiG-23 rather than the MiG-25 it actually is, there may be no penalty at all if the Blue wins the engagement. That is, this less than optimum assessment did not prove critical. What may determine criticality is how close the air combat system must come to making the optimum decision and still survive and complete the assigned mission. The more leeway, the less critical and difficult the task.

Criticality can also be viewed from the point of view of the impact of delaying or extending the time it takes to complete a task. Here, the important issue becomes the time compression effect this has on following events/tasks. The obvious example here is the task of making a target track file in a jammed environment. In general, most future tasks in a mission such as defensive counter-air cannot occur until the track file is set up. Delaying the track file initiation effectly shortens the time available to do the future tasks such as battle planning. Compressing these future events can lead to degraded performance in accomplishing the tasks and ultimately lead to a less effective mission. Another example is locating a fixed target during a deep strike mission. Delays in detection can lead to increased exposure of the aircraft and a less than optimum approach angle to the target. At worse case, it can eliminate any chance at a first pass kill.

Finally, criticality can be considered from the viewpoint of the consequences of failing a task completely. In some cases, for instance overflying a waypoint or navigating improperly, the impact may mean mission failure because the aircraft does not reach the target at the intended time. However, it does not necessarily mean the aircraft will be killed. Alternatively, a failure to employ defensive measures

against an inbound missile may indeed mean the aircraft is killed. In this context, clearly the second case is more critical given the need to survive.

With all these considerations in mind, current experienced tactical pilots were interviewed to determine their opinion of the most critical tasks (Reference 9 and 20). In roughly chronological order, they include:

- * takeoff
- * sensor management to maximize coverage
- * achieving early target track
- * target ID
- * maneuvering for tactical advantage
- * launch at optimum range/conditions
- * predict enemy tactics
- * select and execute action against adversary's air-to-air missiles
- * detect/sense SAM's
- * select and execute action against inbound SAM
- * effective masking
- * locate runway and land
- * fault detection
- * required communications at all stages of missions

3.3.3 Summary

The previous sections have identified those tasks deemed by pilots to be the most difficult and critical to accomplish in the air combat arena. Some are difficult or critical by the nature of the task (such as precise manual adjustments to equipment in the airborne environment) while others are made difficult by the context in which they must be accomplished (for instance creation of a radar track file in a jammed environment). Remembering that the primary purpose of the Pilot Associate program is to provide information to allow the pilot to make more tactically effective decisions, it makes sense that the program should focus its attentions where improvements will have the greatest impact.

There is significant overlap between those tasks deemed difficult and those most critical to mission success. Clearly, improvement in these areas should lead to a more effective air combat system. The overlap tasks can be roughly grouped into four major groups - those relating to situation awareness, system status, tactics, and those that are more mission related. The following list is but a sample of such tasks.

Situation Awareness Related Tasks

- * Achieving early target track files and additional data on the world of interest about the airplane
- * Overall sensor management particularly given stealth issues
- * Target ID
- * Detect/ID SAMs

System Status Tasks

- * Airplane performance capabilities at any given time
- * Airplane's configuration - current and desired
- * Avionics system capability and performance

Tactics Related Tasks

- * Predicting likely enemy action/response
- * Planning ownship and coordinated tactics
- * Selecting optimum launch conditions
- * Avoidance/defeat of incoming missiles
- * Selecting response to detected SAMs

Mission Related Tasks

- * Selecting new flight path/profiles i.e., mission replanning or repair
- * Effective masking (TF/TA)
- * Target re-prioritization under conflict

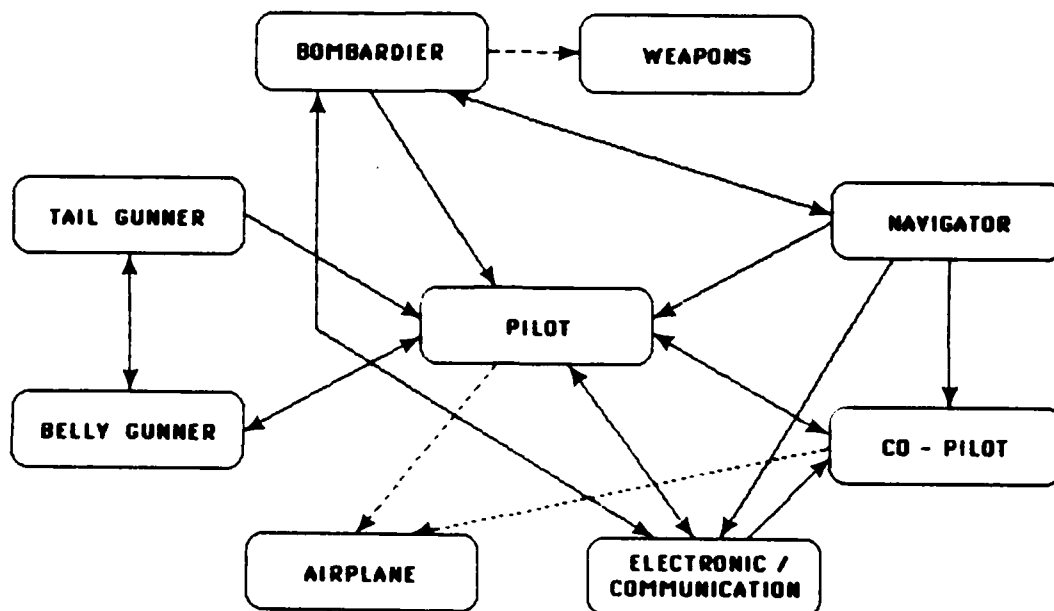
One final task that does not conveniently fall into any of the above categories is communication. Reference 20 indicated that communication is often the first item that suffers lack of attention from the pilot as a situation "heats up." Yet, pilots recognize the need for coordination among their flight to optimize combined system effectiveness. In today's fighters, the audio environment is badly cluttered with superfluous information that is essentially unfiltered prior to reaching the pilot. How tomorrow's pilot receives the

information he needs - both from outside sources as well as his own systems - will go a long way toward determining his effectiveness.

Today's technology has brought us to the point where a pilot no longer suffers from lack of information. Sensor and processing advancements have resulted in a situation where he cannot absorb all the data/information that could be provided. Substantial processing must be done prior to presenting information to the pilot and then the transfer must be effective, easily interpreted, and flexible. Otherwise, improvements in any or all of the areas listed above may be wasted. Indeed, methods of presenting information to the pilot is probably one of the most crucial factors in improving system effectiveness.

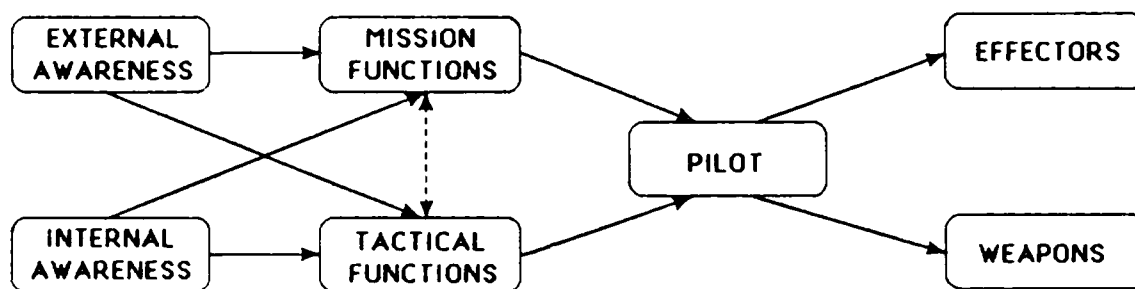
There are several ways one can summarize the principal processes supporting all of the mission tasks discussed in preceding sections. First, it may be considered to base process definitions on descriptions of human processors from prior systems. Figure 15 illustrates such a system where the processors are functional clones of the human counterparts. For humans, this approach had merit because of the high degree of sophistication and adaptability of each of the processors. It demands high bandwidth symbolic interchange of data among all of the processors for the system as a whole to be successful. But it has severe limitations if a one-for-one substitution is attempted using artificial intelligence techniques in place of human intelligence. A more adaptable approach is suggested in Figure 16 where the same system functions can be accomplished as in the system of Figure 15 but the processes are organized in a manner minimizing inter-processor communication.

If we apply this reasoning to processes involved in air combat systems and their architecture we might see something like the process architecture partially developed in Figure 17. Here, space prevents showing full development of the architecture, but the degree of development shown should be sufficient to convey the idea. Note that in almost all cases the initial process in any chain is generating perceptions of the current world situations.



EACH ELEMENT :
 • GATHERS DATA
 • PROCESS DATA
 • COORDIANATES
 • TAKES ACTION

Figure 15 Human Role Based Information Processing System Definition



- EACH ELEMENT:
- HAS CONCENTRATED RELATED PROCESSING
 - DIRECTIONAL DATA/INFORMATION FLOW
 - MINIMUM LATERAL/REVERSE INTERFACE

Figure 16 Goal Directed Information Processing System

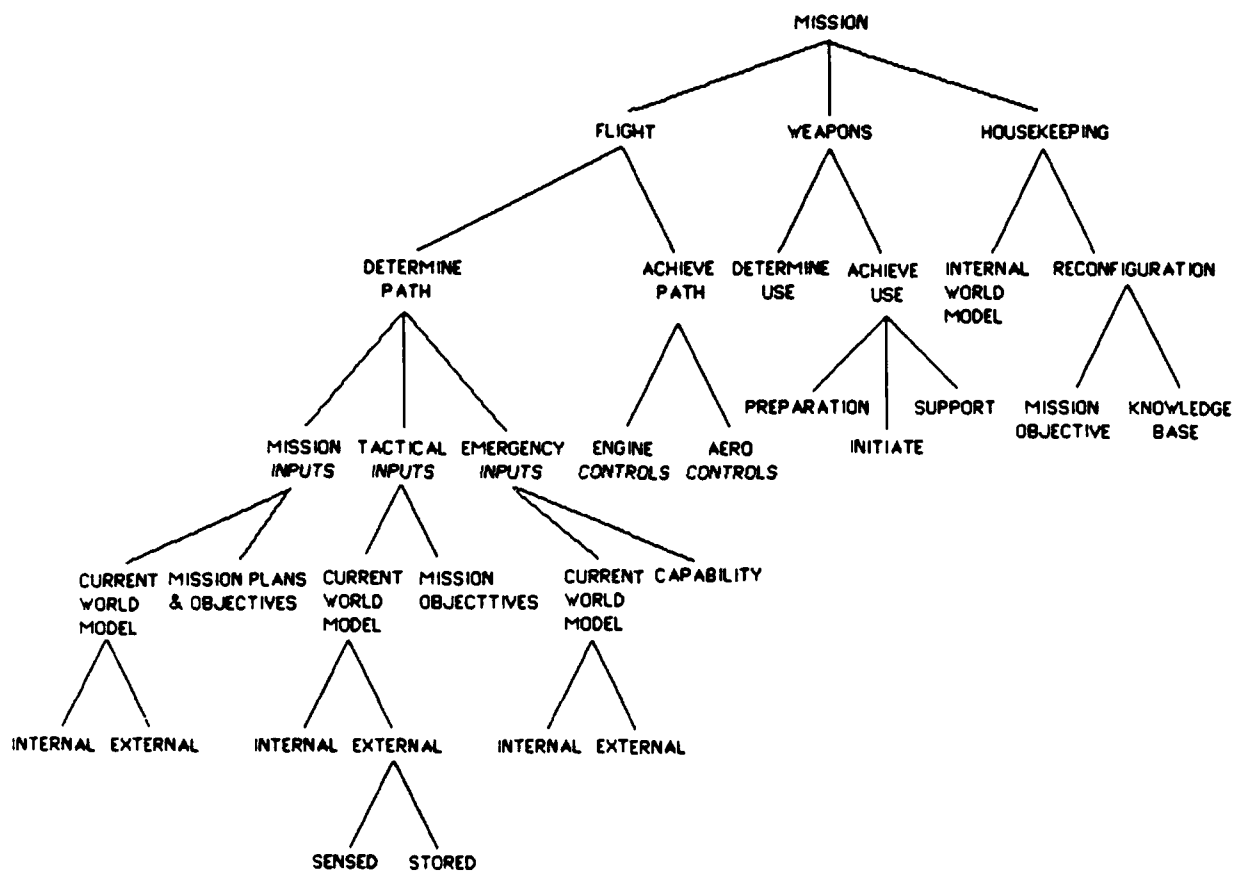


Figure 17 Air Combat System Process Architecture (Partial) Diagram

SECTION 4

PILOT'S ASSOCIATE

Primary functions of the Pilot's Associate are to generate information from available data sources, make assessments and draw conclusions in time domains inaccessible to the pilot, initiate direct action where human response time is limiting, and provide the pilot/crew with selected data/information in a manner that incorporates the pilot in the system in the most efficient manner. Its objective is to ensure that, from the system as a whole, the most tactically effective decision will always be made during combat. It should be noted that the Pilot's Associate is not a piece of equipment - it is a highly sophisticated information processing system and its formal representation resides in both a complex of parallel and serial digital <6> processing hardware and a variety of software codes. <7>

As noted in Section 2, for large complex information processing systems, major processes need to be defined in a manner permitting growth, efficiency of operation, and consistent with an overall architectural scheme. The requirement of an airborne combat system fits this mold. Therefore, the first task is to identify a set of preliminary definitions and rationale for the first tier of processors within the Pilot's Associate.

Preliminary analyses have shown that the major processes to be performed by the system can be correlated by the time in which they must be executed into several basic elements. Since processing dynamic range is a consideration within a processor, there appears to be a natural fit if the processor is partitioned along these lines. In addition, the criterion of minimal inter processor data bandwidth must be maintained as the definitions are developed. At the highest frequency end of the processing spectrum are those processes related to sensing and describing the environmental world in which the system is operating.

That world can be further divided into internal and external components because of major differences in sensor systems used to accumulate data. The internal world can be sensed directly while the external world must use sophisticated techniques to obtain data by measuring characteristics of radiant energy either generated by the environment or reflected by the environment from energy transmitted by the system itself or an associate.

Measurement, analysis, and subsequent evaluation of the received energy becomes an enormous task when significant volumes of space are interrogated over wide frequency ranges. Tactically, it is necessary that this process of environment awareness must be accomplished in a time frame of milliseconds-seconds to a few seconds. Thus, two major elements of the Pilot's Associate are now defined as the System Status Manager (SSM) - a major processor which senses internal environment, and

<6>. And possibly analog.

<7>. Often interrelated.

the Situation Awareness Manager (SAM), a major processor that senses the external environment. Within these processors, event times are measured in milliseconds-seconds to seconds with decision windows of milliseconds to milliseconds-seconds.

At the next level of processing timeliness is assessment of the environmental situation to determine its tactical and mission significance. From the tactical standpoint this includes generating and evaluating tactical options for pilot review and action, or in time critical situations, for initiating action directly <8> but keeping the pilot informed. At aircraft speeds the event times available for such tactical analysis, evaluation, decision and execution is in the fractional second to minute time span, and decision windows cover the milliseconds-second to second range. This major processor becomes the third element of the Pilot's Associate called the Tactical Manager (TM).

The longest time available for functional considerations involves evaluating mission objectives and plans, comparing them with the sensed world situation and generating alternatives for pilot consideration. These functions span event times of minutes to hours. Decision windows within these event time range from seconds to minutes. This is the fourth element of the Pilot's Associate and is called the Mission Manager (MM).

Each of the preceding four major processors has a requirement to communicate with each of the others through minimum information bandwidth channels and to communicate with the pilot. This is in keeping with the notion that the air combat system is just that - a system of sensors, processors, and action/effector systems. The processing part of the system is an integral of machine and human capabilities using each capability when and where necessary with a minimum of isolated responsibility. Communication between machine processors and the human processor must maintain this philosophy if the overall system is to achieve maximum utility.

Communication needs vary among the processors from relatively simple for the System Status Manager to quite complex for the other managers. These needs must be reflected in the fifth element of the Pilot's Associate, the Pilot/Vehicle Interface (PVI).

Figure 18 illustrates this embodiment of the Pilot's Associate concept as it relates to other elements of the system.

Analysis of the missions described in Section 3 shows that the problem of data overload on the pilot occurs in all of them to some degree. It becomes evident that the entire spectrum of anti-air warfare could benefit from some level of increased processing capability in the weapon system. The conceptual structure of a Pilot's Associate, as discussed above, has been designed to provide as much functional isolation among elements as possible so that their development could progress relatively independently as the emergence of processing

<8>. With prior concurrence of the pilot.

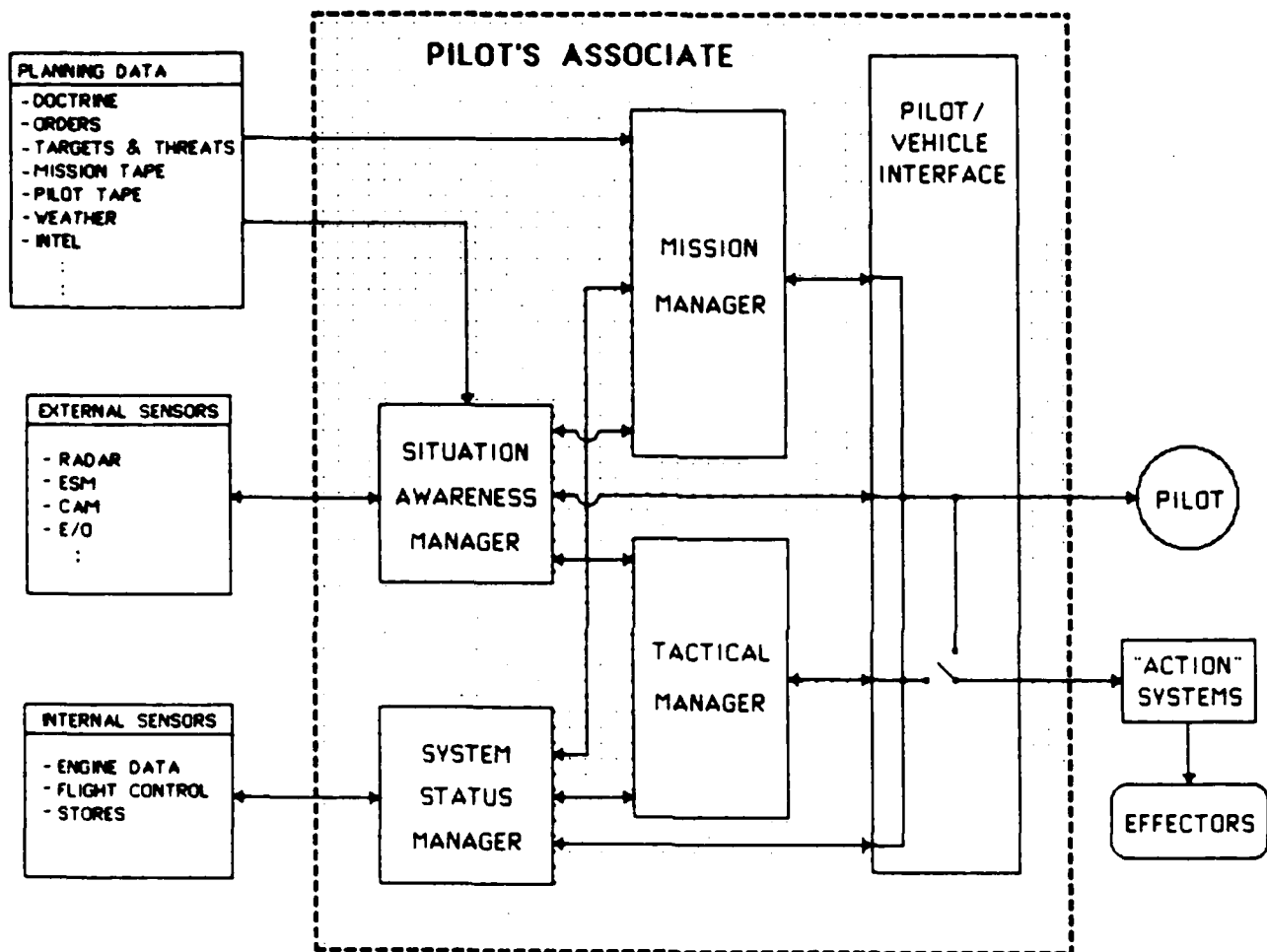


Figure 18 Pilot's Associate Block Diagram

technology permits. Each of these elements is discussed in some detail in the following sections.

4.1 SITUATION AWARENESS MANAGER

4.1.1 General Description

The Situation Awareness Manager has one function; to provide the pilot and other major processors with as complete and current a description (model) of the current external world as possible. Figure 19 presents a data/information flow block diagram of the SAM for a generalized aircraft showing the primary processes needed to provide the required data. The essential output of the SAM is the basic data set for each object and groups of objects held in the current external world model (EWM). At the object level, the basic data set consists of:

- 1) State Vectors - Each object's present position, velocity and (if possible) acceleration are described by a vector set in a predetermined coordinate system used by all of the processors on board the aircraft as a reference.
- 2) Data Flags - Additional data, generally scalar in the broad sense, about each object containing the following typical information:
 - * Identification
 - * Classification
 - * Source
 - * Confidence
 - * Accuracy

As shown on Figure 20 these data are compiled by a sequential processing system beginning with conventional signal processing behind each sensor through analysis, evaluation, and management processing. Their internal functions are characterized, in part, by:

- a) ESM Signal analysis
- b) Correlation, Identification and Classification
- c) Sensor Allocation and Management

These typical subprocessors are described in the following sections.

4.1.2 Electronic Support Measures (ESM) Signal Analysis

The function served by the ESM Signal Analysis subprocessor is to provide an identification of rf signal sources and their bearing (sometimes elevation also) from the weapon system platform. Four

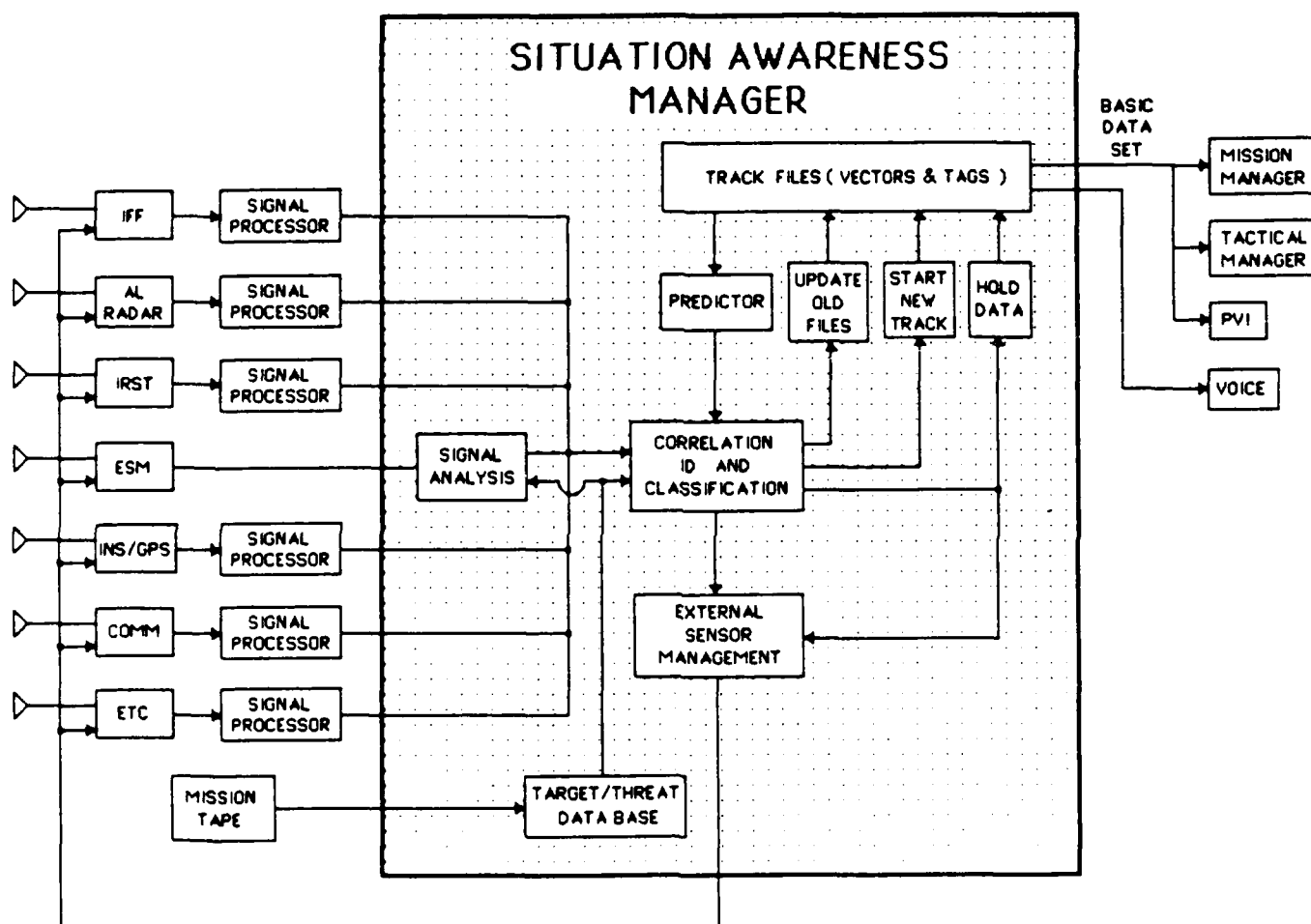


Figure 19 Situation Awareness Manager Block Diagram

definitive processes are involved; planning, monitoring, prediction, and interpretation. Because of the large number of options for identification and temporal frailty of the signals, large amounts of very high speed parallel processing (systolic machines) will be required.

The source of rf signals can be any of 60 (or more) airborne transmitters, on any of 80 different types of aircraft (one or more per aircraft - up to five or six), and up to 75 to 100 different types of ground based transmitters. Some of these are friendly, some not, and some are neutral sources. Airborne source platforms are made up of about 60 airplane types and 20 helicopters. Ground sources include data links, voice links, search radars, tracking radars, command links, all both military and civilian as are the airborne platforms.

In order to perform its functions, the ESM signal analyzer will require an extensive data base including characteristics data for every sensor which could be encountered during a mission. This data base will be loaded along with a mission tape during preflight preparation. The mission tape contains all mission peculiar data/information the pilot and machine will need to know. With respect to signal data, as a minimum, it must contain the following types of data:

- * Signal attributes
- * Operational doctrine
- * Proximity to other sources
- * Operational anomalies
- * Transmitter/platform combinations
- * Geographic locations
- * Language recognition data base
- * Data link protocols
- * Standard data transmissions

4.1.3 Correlation, Identification, and Classification

The function of this subprocessor is to confirm, from multiple sensor data and data held in the track files, the state vectors of all objects of interest in the weapon system's external environment, and to associate with these vectors scalar information, or "tags" conveying such information as the object's identification (friend, foe, neutral), intent (mission objective, if applicable), etc. Three AI processes are used; a) interpretation, prediction, and monitoring.

In more general terms the subprocessor accomplishes the following. It compares new (current) data conveying position and/or velocity information from each sensors with similar data from the other sensors (considering data links such as JTIDS as a sensor for this discussion) to determine which, if any, data sets relate to the same object with sufficient confidence to say they are one and the same. If a correlation is made the result is then compared with similar data stored in a "track file". To correlate the new data with stored data, it is necessary to extrapolate the old data (many techniques exist) to current time for the comparison. If there appears to be a temporal correlation, then the track file data are updated with the new data. If multi-sensor correlation cannot be accomplished to the level of confidence desired,

then temporal correlation is attempted with each data set, remembering how the prior correlation was made.

When correlation is not possible one of two choices remain. Establish a new track if the situation warrants, or put it in a "hold" file for later analysis. After vector correlation is completed (and sometimes in parallel) the data are combined with other data analysis results (ESM for example) and knowledge data bases to determine the scalar quantities desired. These data bases must contain, among others, the following classes of information:

- 1) Airplane characteristic data
- 2) Tactical behavior of enemy and friendly aircraft
- 3) Weapon capabilities, friendly and enemy
- 4) System signatures, radar, IR etc.

4.1.4 Sensor Management

The Sensor Management subprocessor receives information requests from the Correlation, ID, Classification subprocessor, as well as from the other processors, which it must first analyze for feasibility. It must then identify the sensor best suited to gather the requested information. Finally, it must determine the priority of all current requests, assign them an order and initiate the sensor changes required for the top priority information. In order to accomplish these objectives, a data base is required for each sensor including:

- * Sensor operating characteristics
- * Operating times
- * Physical limitations
- * Evaluation models

It should be noted that the Sensor Management subprocessor will have to be interfaced with the pilot to permit direct inputs from him for information. His input must then interface with the same processing that system internal requests undergo so that the pilot can be advised of other requests and their priority and of the feasibility of obtaining the data requested by him.

4.2 SYSTEM STATUS MANAGER

The System Status Manager interfaces with two environments; pre-flight and in-flight. In pre-flight it is used in conjunction with the system's GROUND SUPPORT EQUIPMENT (GSE) to perform pre-flight checks and to obtain current and historic system status information. Its primary use is airborne, and descriptions of those functions and processes are subjects of the following paragraphs. In-flight it must monitor on-board system status (health), to provide continuous system capability and limitation data to the other managers for their use. It must notify the pilot of out-of-tolerance conditions, and take appropriate corrective action if required. In short, it serves to provide the

- 4.0 Weather (by route segments)
 - 4.1 Wind data by altitude levels (4)
 - 4.2 Precipitation
 - 4.3 Cloud cover
- 5.0 Friendly Resources
 - 5.1 Escorts
 - 5.2 Ingress-Egress corridors
 - 5.3 SAMs
 - 5.4 C-Cubed centers (3 to 5)
- 6.0 Communication Protocol
 - 6.1 AWACS
 - 6.1 US Fighters
 - 6.2 NATO Fighters
 - 6.3 Air-to-Ground Aircraft
- 7.0 Electromagnetic Environment
 - 7.1 Source 1 (type)
 - 7.2 Source 2 (up to 100 types)
- 8.0 Mission Option Data
 - 8.1 Airfields (friendly)
 - 8.2 Airfields (enemy)
- 9.0 Route Planning (by segment)
 - 9.1 Terrain maps for route and alternate segments
 - 9.2 Flight route, primary
 - 9.3 Alternate routes by segment (up to 4 per segment)
 - 9.4 Integration of route data with other data depends on the conceptual structure of the pilot-vehicle interface.
- 10.0 Crew briefings and Mission Preparation
 - 10.1 Minimum time available
 - 10.2 Nominal time available
 - 10.3 Long preparation time available
- 11.0 Maintenance and Replenishment Requirements
 - 11.1 Equipment mode settings
 - 11.2 Subsystem special tapes (ESM, sensor processing, etc.)
 - 11.3 Compilation of maintenance data for mission tape
 - 11.4 Armament load
 - 11.5 Fire control tapes
 - 11.6 Expendables

with both serial and parallel processing capability to permit simultaneous examination of several option paths. In addition, it will be necessary to develop a core data base for the SPOG to provide the evaluation criteria needed.

The above description treats the Mission Manager as though it were a batch processor, operating a frame at a time. Such a mode of operation would probably be satisfactory for processing routine data (expected events), it would probably not be acceptable for unexpected events since the reaction time could be longer than that required to handle emergencies. The manager will have to be designed as a parallel processor with sufficient channels to handle the largest number of unexpected phenomena anticipated. In addition, there should be an evaluator which ranks unexpected events by their implicit danger so that the least dangerous ones could be relegated to the batch processor in the event of an overload.

4.4.2 Mission Planner

The mission monitoring, analysis and option generation functions to be performed require a well coordinated pre-mission planning effort to produce the tape(s) required as part of the data bank. In addition, material must be prepared for pre-mission crew briefings and training, and as instructions for the ground and maintenance crews to prepare and arm the airplane for the mission. It is anticipated that some level of expert system will be required by this pre-planning system, however, it is estimated that it will not be a major development problem since it will not be required to operate in real time.

Following are category estimates of the data bank requirements for the pre-mission tape and instruction material generation and of the processing requirements of the Situation Analyzer and Situation Processor and Option Generator in the airplane.

Data Bank Requirements

1.0 Target Data

- 1.1 Number during mission (3 to 4)
- 1.2 Description
- 1.3 Location in North/East/Altitude coordinates
- 1.4 Weapon Use (data for each target) (see 11.0)

2.0 Air Threat Data

- 2.1 Base locations (4 to 6 bases, North/East/Altitude)
- 2.2 Numbers and Types of aircraft
- 2.3 Tactical policy

3.0 Ground Threat Data

- 3.1 Type 1 (e.g. SA 6)
- 3.2 Next Type (up to 20 per mission)

Status or Situation Awareness) for action through their sensor requirements functions.

All processed information considered critical is then sent to the situation processor and option generator (SPOG). It is here that the greatest degree of AI and sophisticated conventional processing will be required. The option generator processes all of the information available to it to determine alternative mission options which combine the highest probability of operational payoff (in terms of targets destroyed) and the highest probability of survival for the system. These alternatives are prioritized and sent to the pilot for his consideration. Depending on the decision made, the appropriate changes are made in the mission plan and in the associated data banks. Action as required to implement the decision is initiated either by the pilot or by the Manager as desired and the mission proceeds.

For example, consider the system processes which must be carried out in the event of a system failure due to a malfunction or combat damage. Assuming that the failure is severe, and that the mission must be aborted, the SPOG first calculates the flight time available, and the effect of the failure on flight controls and landing systems. It then looks for a landing field which has the following characteristics in order of priority:

- * It is the closest to home base considering fuel reserves.
- * It has a runway which is long enough considering any landing system damage.
- * It has repair and replenishment facilities as needed by failed/damaged systems.

If no field fully meets the needs, the SPOG evaluates the danger associated with the discrepancy(s) (the runway is too short, but the damage sustained using it would be minimal). If no field is acceptable, the SPOG researches the enemy field file for the "best" alternate by evaluating the physical properties with location and "escapability".

Other type of mission redirection which would handled by the SPOG could include:

- a) Selection of an alternate target(s) due to weather, unexpected enemy defenses or other reasons.
- b) Selection of an alternate route due to unexpected SAMs, weather etc.
- c) The selection of alternate weapons due to malfunction, route changed approach not conducive to the pre-selected primary etc.

The list of possible processing requirements is very large, involving permutations and combinations of all damage and/or failure possibilities. Consequently, it will be necessary to structure the SPOG

- 2) Using the present position, location and characteristics of objects identified by the sensors are compared with planned intercepts/detections.
- 3) Objects not in the plan are examined to establish their relationship with the mission and with other objects already noted. Information is then derived about their potential interaction with the mission.
- 4) The absence of objects listed in the mission plan which are within range of the sensors but have not been detected is analyzed to determine significance. Inferences drawn are added to the unexpected data files for further analysis.
- 5) System status, as reported by the System Status Manager, is continuously monitored and ownship capabilities are compared with mission requirements. Unusual or out-of-tolerance conditions are also entered in the unexpected data files.
- 6) Information in the unexpected data files, together with data on their correlation with the mission are analyzed to determine their relation to the mission; are they threats? If so, how dangerous?; are they potential targets? If so how valuable?; have they any intelligence value? etc.
- 7) Information so derived is sent to the pilot if it is considered critical, to the Processor and Options Generator if it is serious, and to the data bank if it is considered information worth storing.
- 8) All out of tolerance conditions are analyzed to determine if they would impede completion of the mission. If not, the pilot is so notified and the information stored. If the mission is in jeopardy, alternates are examined to determine feasibility and worth. Selected options are then sent to the pilot for his decision. Given a decision, the Mission Manager alters its mission files and informs the rest of the Pilot's Associate of the changes.
- 9) The data bank is then updated with new and confirmed old data, and the mission progresses as defined.

Within the Mission Manager are analysis functions similar to those in the System Status Manager. A comparative analyzer that determines the degree of similarity between the planned (or replanned) mission and the immediate real world. A trend predictor estimates future tolerance problems for parameters within tolerance but with rates of change that anticipate an out-of-tolerance condition in the near future. An out-of-tolerance analyzer determines the nature and the severity of any out-of-tolerance situations that arise. The need for additional data from any of these processors is sent to the appropriate Manager (System

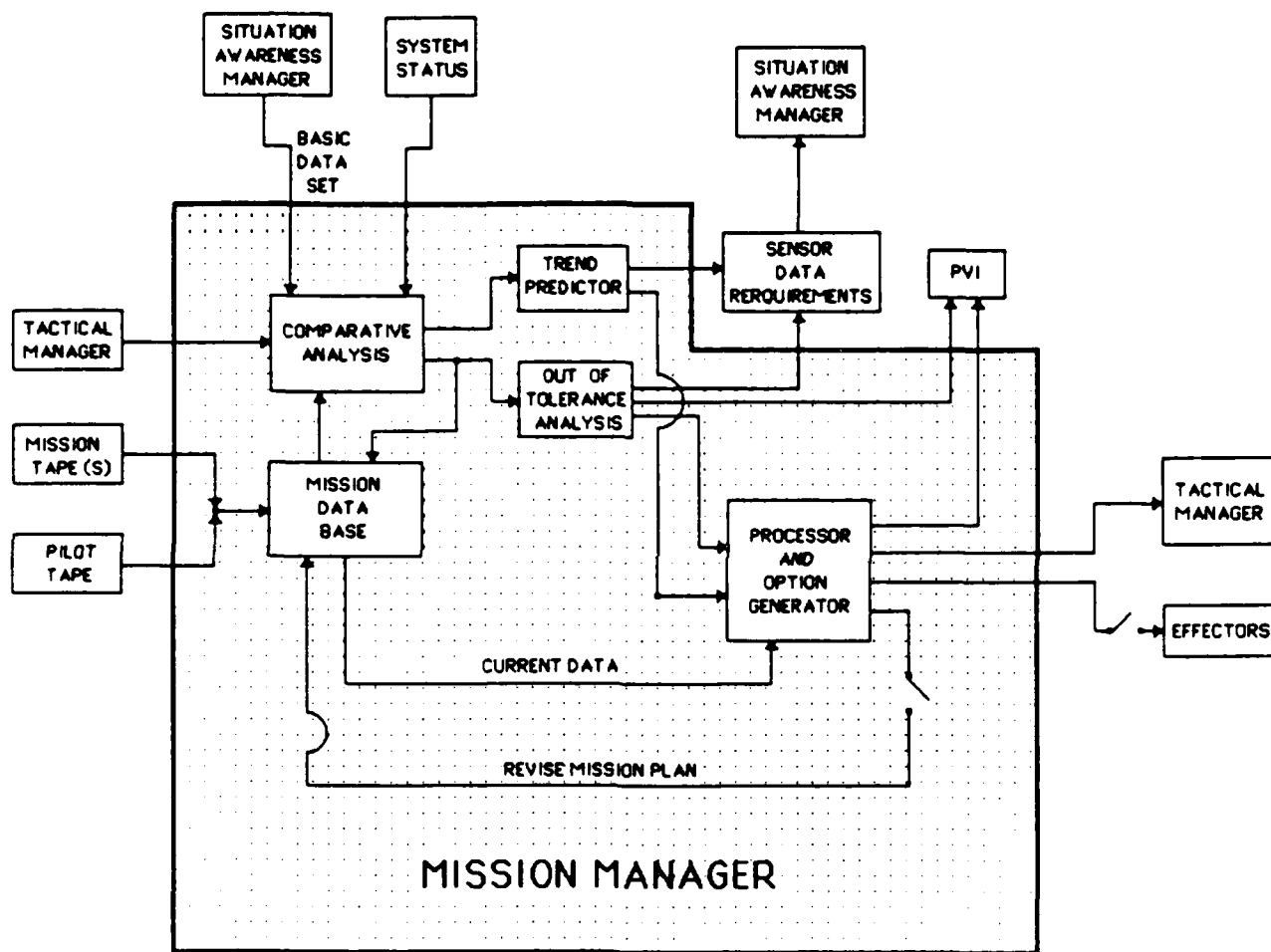


Figure 22 Mission Manager Block Diagram

by the Mission tape. These needs are discussed in the following paragraphs:

Threat/Target Analyzers - Two types of data bases are required in these subprocessors, the first consists primarily of algorithms modeling the performance characteristics of enemy aircraft and weapons expected throughout the mission, and of algorithms modeling own-ship and other friendly's performance. In support of these algorithms must be a tactics file based on the type of aircraft, the location of the combat, known information regarding the pilots at the probable base of origin of the threat and a basic data bank of typical aircraft tactical maneuvers. These data are combined to identify a specific tactic for use by the predictive algorithms.

Option Generator - The option generator uses primarily a data base of internal and ownship data regarding fuel status, armament load, maneuverability etc. together with tactical preference information loaded into the subprocessor by each pilot as part of his mission preparation sequence. This data base will be continually updated by the SSM to insure currency of data being used to generate and select tactical options for evaluation.

Tactical Analyzer and Evaluator - this subprocessor will have very little in the way of inherent data base other than evaluation criteria as appropriate to its processing function. Although many of these criteria will remain constant, some will be adjusted in accordance with specific mission objectives. In particular, kill and survival probabilities may change depending on the tactical significance of the mission being conducted.

The TM's primary interface is with the PVI and the action system since it provides a spectrum of information needed to make optimum tactical decisions. It is important that the nature of the PVI be established in conjunction with processing requirements of the TM to insure that information generated is selected and formatted properly for communication with the pilot.

4.4 MISSION MANAGER

4.4.1 General Description

The Mission Manager illustrated in Figure 22 continuously monitors mission progress against pre-planned information from a mission tape along with modifications to that plan made earlier in the mission. As long as the mission remains within prescribed tolerances, it informs the pilot that everything is progressing normally. This function can be performed in the following steps:

- 1) Aircraft navigation data (north, east and altitude) is used to locate ownship on the planned route, noting any errors or out of tolerance deviations.

4.3.4 Input Data Requirements

Data required by the Tactical Manager will be provided by the SAM and the SSM, each making available its basic data set on the external and internal worlds respectively. It is the external world data that are most critical to the Tactical Analyzer since it provides the parameters used in predicting future tactical world models. The following paragraphs discuss some of the contents of the basic data set generated by the SAM with emphasis on their priority and use:

- 1) State Vectors - Position and velocity vectors are mandatory if future tracks are to be predicted with reasonable accuracy. Approximations can be made using bearing data (for example) however, it requires integration times so long that it would be of value only at long ranges, since event rates at close ranges would exceed the prediction rates. Additional data such as acceleration vectors, target attitude etc. would permit further refining of object track prediction.
- 2) Classification - Prediction of the level of a threat or value of a target requires that the type of aircraft (or other target) be known and that a reasonable estimate can be made about its armament. Without these data, ownship in-weapon-release-zone position relative to a threat cannot be computed, nor can accurate estimates be made of a threat or target's evasive capability. In addition, classification data permit consideration of non-lethal weapon (ECM, flares, etc.) use based on the avionics suite carried by the threat aircraft.
- 3) Identification - Depending on the Rules Of Engagement (ROE), identification may be mandatory if lethal weapons are to be used. In any event, identification is desirable information to have to minimize the probability of attacking a friendly. Furthermore, the level of confidence in ID should be associated with the identification information to facilitate assessment by the pilot.

Finally, the combination of identification and classification greatly increase the selection of realistic tactics for use in the predictor with a resultant increase in the validity of future states generated.

- 4) Other Data - The remaining data in the basic data set provide increased confidence that the predicted world is accurate. Sensor information can be used to request additional data from the same or other sensors, while confidence data will be used by the pilot in his decision process.

4.3.5 Data Base Requirements

Each of the individual subprocessors in the Tactical Manager will require some form of data base depending on its function. Much of the data base required will be peculiar to the specific mission being conducted and will be loaded into the appropriate processing system

4.3.1 Target/Threat Analysis

Although there are two functions shown, air and ground, their processing requirements are quite similar. The primary function performed by these subprocessors is to develop measures of the degree to which a tracked object could be considered either a threat or a target and to estimate states for each at some future time.

Basic data sets representing the EWM from the SAM, and own-ship status from the SSM are combined to develop future states and measures required for tactical analysis. These subprocesses assume a tactical doctrine and intent for each threat and the prediction of its future state based on those assumptions. For objects identified as targets, the subprocessor must predict future attack conditions based on similar assumptions regarding the target's tactics and intent as well as its own-ship state status.

4.3.2 Tactical Option Generator

Based on future state calculations from the Air and Ground Target/Threat Analysis subprocessors, the Tactical Option Generator determines possible flight path and weapon options for own-ship. These options are also based on pre-determined criteria for offensive execution compared with its probability of survival.

4.3.3 Tactical Situation Analysis and Evaluation

The most sophisticated of the subprocessors in the Tactical Manager is charged with the task of evaluating the future states proposed by the Target/Threat Analyzers and the Tactical Option Generator. Outcome of an anticipated engagement between own-ship and the threats and/or targets must be predicted, evaluated and weighted. Results of this process for each reasonable option are then presented to the pilot for his consideration and decision. As indicated before, provision must also be made for the TM to evaluate its own recommendations and initiate appropriate action if warranted. Obviously, provision must be made for appropriate feedbacks, particularly from the pilot to the TM requesting additional or different information.

Detail study of the processing technology needed to develop the Tactical Analyzer, for example, is beyond the scope of this study. It will be necessary to conduct a thorough conceptual design of the analyzer so that the nature and extent of the processing technology required is understood and can be specified as research and development goals. The architecture presented in Figure 21 has been designed to accommodate this, by allowing preliminary versions of the Tactical Manager to be developed and made usefully operational. Lower levels of analyzer sophistication could go directly to the Pilot-Vehicle Interface (PVI). As improved information processing capability becomes available, increasing levels of sophistication could be implemented providing the pilot with the best prediction of threat behavior for all targets held in the track file. Its validity would be limited by the quality of data received from the SAM and by the level of an on-line evaluation available; however, it would still provide the pilot with considerably better information than presently available.

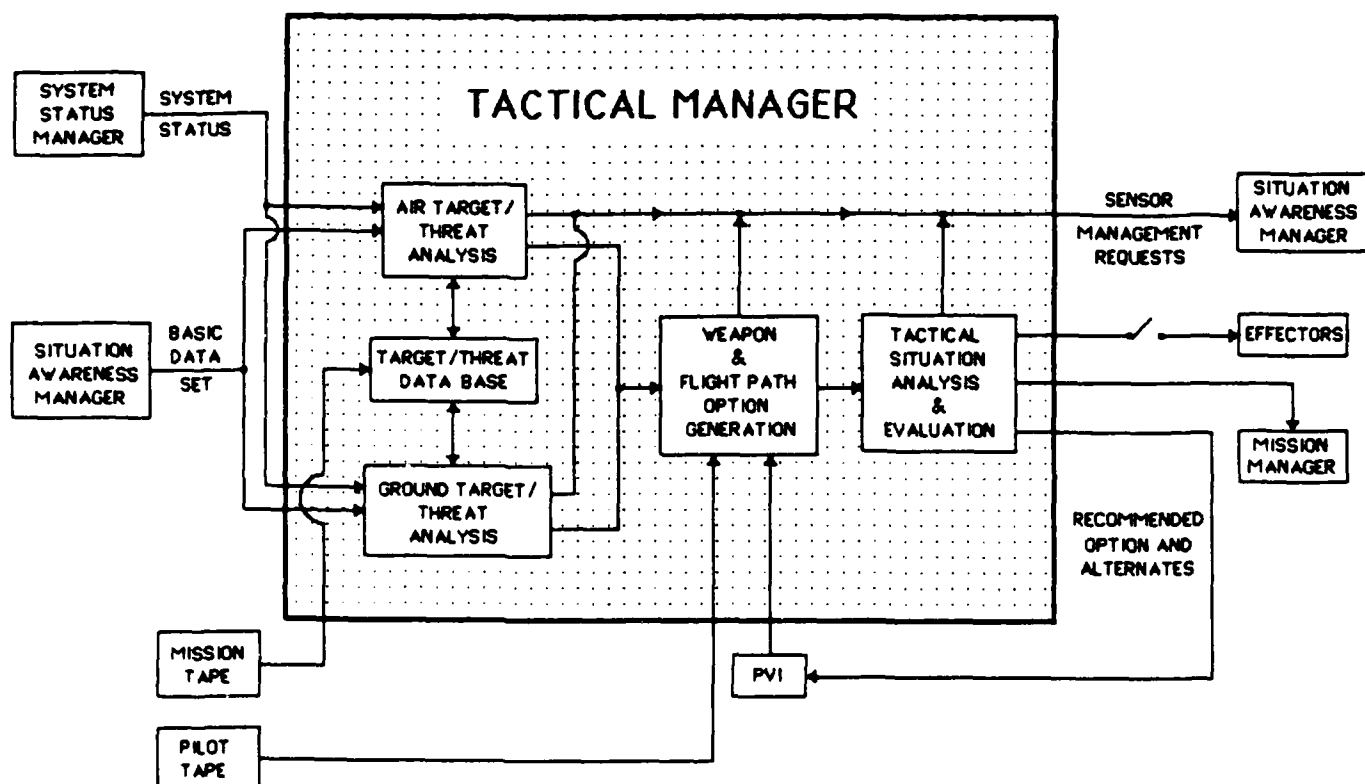


Figure 21 Tactical Manager Block Diagram

status is always current. Following is a sample form for collecting and entering data into the data base:

Parameter	No. of Items	Type of Measurement	No. of Meas.	Frequency of Meas.
Water Injection	1	On-off, flow rate	1	1 sec
Bypass System	1	Exit pressure	3	10 sec
RPM	1	Rotational speed	1	1 sec
Temperature	1	Temperature	10	5 sec
Lubricants	3	Pressure	1	2 sec
		Quantity	1	5 sec
		Control System Error	1	1 sec
Thrust	1	Strain gages	4	10 sec
Fuel flow	1	Flow rate/nozzle	4	5 sec
Control systems	3	System error	3	1 sec
Inlet Configuration	3	1 Position, 2 Angles	3	30 sec
Torque	1	Shaft strain gages	4	5 sec

4.3 TACTICAL MANAGER

The Tactical Manager is the most sophisticated element of the Pilot's Associate, requiring the highest level of intelligent information processing. It must absorb information provided by the SAM, predict realistic future tactical situations, and determine tactical options for the pilot providing a maximum balance between his ability to destroy the enemy and to survive. It must also be capable of making decisions for the pilot if he is in an overload condition. Processor complexity varies from handling an attack on a single, undefended ground target to a high density air engagement involving multiple friendly and enemy aircraft.

The Tactical Manager, as presented here is assumed to be part of the Pilot's Associate for an advanced, multimode aircraft capable of simultaneous air and ground warfare. The diagram shown on Figure 21 summarizes the primary processes to be performed. It has been simplified since there has been only a limited amount of study directed toward defining the underlying process architecture. The figure shows a breakdown of processes into three major processors which are discussed in the following sections.

4) Structures

- a) Strain/Stress Gauges
- b) Vibration
- c) Temperature
- d) Warning systems (e.g., shakers)

5) Stores Position and Status

- a) Bombs
- b) Rockets
- c) Missiles
- d) Bullets/shells
- e) Fuel tanks
- f) Chaff/Flares
- g) EW decoys

6) Expendable Fluids/Chemicals

- a) AE chemicals
- b) Fuel(s)
- c) Lubricants
- d) Water
- e) Hydraulic fluids
- f) Coolants (A/C, sensors, weapons)
- g) Oxygen
- h) Fire extinguishers
- i) Compressed air/gases

7) Electro-Mechanical Systems

- a) Wheel brakes
- b) Actuators
- c) Tail hook
- d) Batteries
- e) Power generators
- f) APU's
- g) Power Control Systems

8) Avionics

- a) Control Built-in BIT systems
 - * Radar
 - * Navigation
 - * IRST
 - * Communications
 - * Weapons
 - * IFF
 - * ESM
- b) Software monitoring
- c) Computer hardware
- d) Perform system level tests for non-BIT systems
- e) Bus integrity (digital/analog)
- f) Fused system level tests
- g) Self Monitoring

9) Pilot

- a) Heart
- b) Pulse
- c) Respiration
- d) Vision
- e) Beta waves
- f) Alpha waves
- g) Hearing

4.2.3 Data Base

The data base required for each specific sortie will come from several places. For each type aircraft, there will be a fundamental data base stored in the baseline system model. For each aircraft and for each sortie this list will be supplemented or modified as necessary with data peculiar to the sortie and any special maintenance actions which cause (or could cause) deviations in the basic data set. These data will be processed and held in the Mission Data Base for use. As the sortie progresses, changes to the system as determined by the sensors and evaluated, will be used to update the data banks so that the system

The remaining subprocessors in this manager will use more conventional processing technology which will; however, be quite sophisticated in its own right. The following paragraphs describe some of the functions performed by these subprocessors.

Comparative Data Analysis - Compares monitored variables with predicted values and determines if they are within limits. In some cases, the comparator is given independent variable values from which it computes expected values for dependent variables. For example, given fuel flow, engine speed, etc. it would compute expected outlet temperature(s). Sample rate would be based on criticality, historic data, or both. Historic data, contained in a system status data bank, is maintained with the vehicle and contains both prior flight and ground maintenance data.

System Data Base - All pertinent data about the aircraft, its engines, avionics, weapons etc. is contained in the system data base. Basic data, common to aircraft of a particular type, is permanently resident in the data base. It is supplemented prior to each sortie with mission peculiar data and recent maintenance actions which have altered the system in any way. The data base is continuously updated by the System Status Subprocessor which determines changes in the system. The data base then provides data, as required, by the other processors to perform their functions.

The following sections present a preliminary listing of sensor functions and data base requirements.

4.2. Monitoring

This section presents some of the formal subsystems the System Status Manager will monitor and possibly control. It also suggests some of the parameters of interest in each subsystem.

1) Engines

- | | |
|--------------------|------------------------|
| a) Water injection | f) Lubricants |
| b) Bypass system | g) Fuel consumption |
| c) RPM | h) Control loops |
| d) Temperature(s) | i) Inlet configuration |
| e) Thrust | j) Torque |

2) Aero Configuration

- | | |
|-----------------------------------|-------------------------|
| a) Air Data sensors | e) Thrust Vector System |
| b) Control surfaces (e.g., flaps) | f) SAS |
| c) Wing swing | g) Wheels |
| d) Boundary layer control | h) Brakes |

3) Life Support Systems

- | | |
|---------------------|-------------------------|
| a) Oxygen system | e) Cockpit temperature |
| b) Pressure suit | f) Ejection seat |
| c) Cockpit pressure | g) Cockpit Illumination |
| d) CBW protection | |

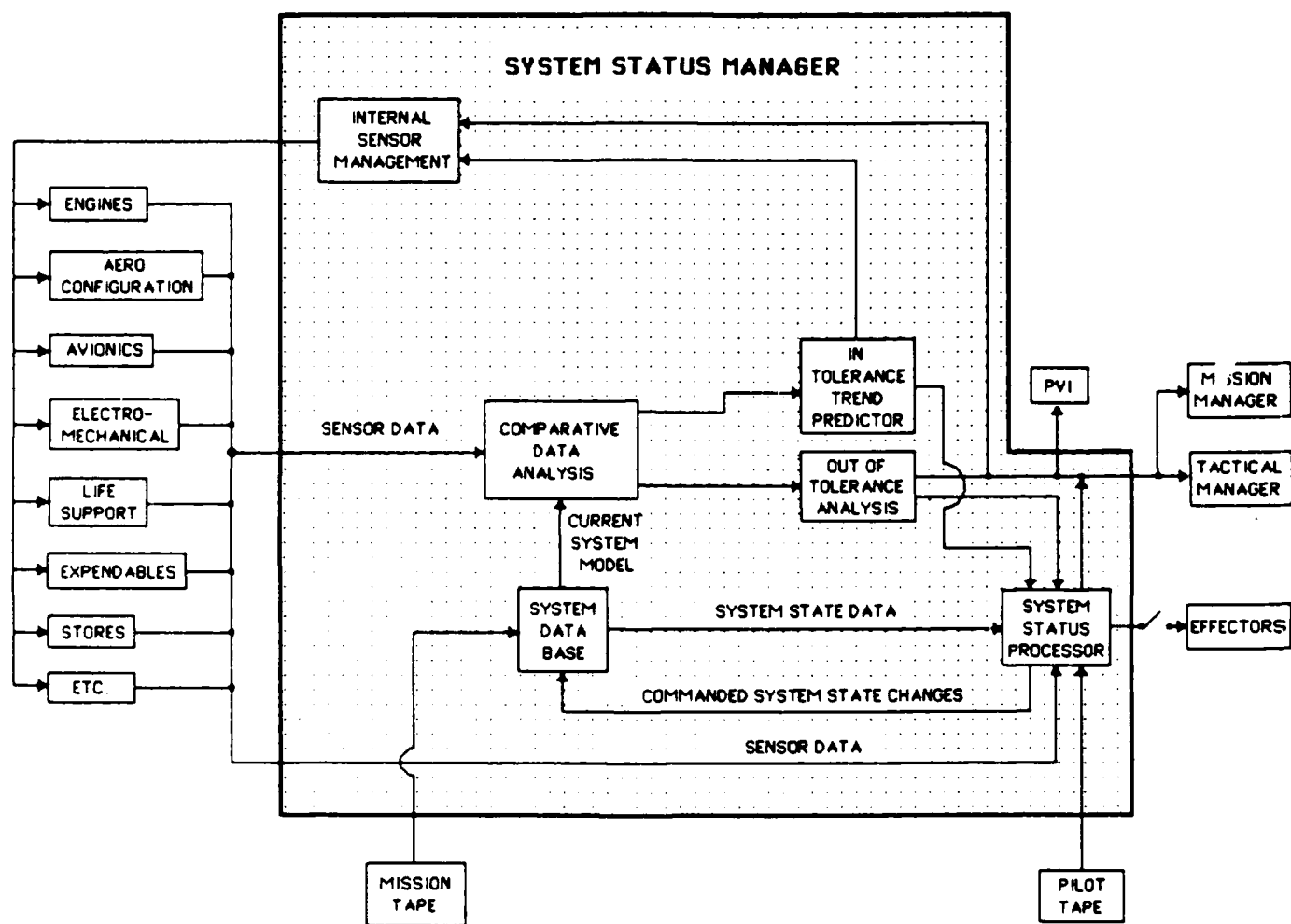


Figure 20 System Status Manager Block Diagram

pilot, and all other internal managers and subprocessors, with a complete and current description of the state of the weapon system and its capabilities.

4.2.1 System Overview

Figure 20 presents a data/information flow block diagram of a System Status Manager. It executes processes and makes available data described in the previous paragraph. Although many of the subprocesses carried out in the System Status Manager use existing technology, there are several elements of the manager which can benefit from machine intelligence to accomplish their objectives. These are:

Trend Predictor - This subprocessor's function is anticipating future out-of-tolerance conditions and requires some expert capability. The trend predictor will permit the system to evaluate conditions and to prepare both the pilot and other major processors for a potentially dangerous condition. It can (must) determine action in advance required to counter the malfunction. In some instances appropriate action, taken in advance of the failure, might prevent a loss of capability from occurring or a catastrophe from happening. In addition, it must maintain an assessment of the airplanes performance capability base resulting from computed trends, and keep the pilot informed of when and where they differ from standard. This includes effects of battle damage.

Internal Sensor Management - Under normal conditions, the sensor system on board the airplane will be programmed to obtain its data in a prescribed manner depending on the system being monitored. In the event an out-of-tolerance condition is predicted, or a malfunction occurs, the sensor manager could adjust the appropriate sensor sampling pattern to acquire additional data as required to analyze and understand the emergency. It is anticipated that intelligent system technology will be required to accomplish the more sophisticated analysis needs.

Out-of-Tolerance Analysis - The analyses performed by this subprocessor deal primarily with the severity of out-of-tolerance conditions and with action required to compensate for them - including the speed of execution required. In effect, this subprocessor represents the human function of conditioned response or reflexive action. It executes those actions requiring immediate attention which cannot wait for a cognitive process to take place.

System Status Subprocessor - This is probably the most sophisticated element in SSM, requiring the highest level of AI to analyze the large number of potentially dangerous situations which could be created by system malfunction or some form of battle damage. It must evaluate situations, postulate solutions or options, compute their implications, dispense appropriate information to the pilot and major processors and respond to requests for information or data from any or all of them. The subprocessor must also update the system data base to reflect changes in status and performance resulting from malfunction, damage or other causes.

4.5 PILOT-VEHICLE INTERFACE (PVI)

A diagram for the PVI is shown on Figure 23. The concept shown has been selected for illustration only purposes in this report and should be considered only as a starting point for the PVI design.

Before examining the PVI structure illustrated, there are some fundamental conceptual changes from conventional approaches to PVI designs which should be discussed. First, and most critical is the nature of the communication to be carried on between the Pilot's Associate and the pilot. Present systems present data about the internal and external environment. These data are then assimilated and integrated by the pilot to form information, analyzed and then acted upon by him. Since the need for a Pilot's Associate has been created, in part, by an excess of data, its primary function must be to process those data into information for consideration by the pilot. Thus, the PVI must communicate information, not data, if its objective is to be accomplished. This represents a major change in the conceptual nature of the PVI requiring careful consideration during the design phase of the program.

4.5.1 Prioritization

Inputs to the PVI will come from the four Managers of the Pilot's Associate. The first function performed by the PVI is to analyze and evaluate the incoming information for criticality in accordance with pre-set criteria established for each mission. Results of this process would be an ordered sequence for presentation of information to the pilot. During early phases of the development program it will also be necessary to give the pilot an information menu to permit sequence evaluation.

4.5.2 Translating and Formatting

The Translating and Formatting subprocessor interprets prioritized information from the managers, and translates and formats results into appropriate symbolism for the type of information to be communicated. The formatted information can then be displayed to the pilot on the appropriate cue. The amount of time available for presenting any information to the pilot may be limited considering the pace of events and the wealth of information available for presentation. There must be a limit -- pilot action, time or some other criterion for the duration of the display so that other information can be communicated.

4.5.3 Pilot Inputs

Having made his decision, if action is required the pilot must input appropriate command(s) to the action/effector system directly (via the PVI) or to the Managers to accomplish his objectives. This process requires two distinct steps which may or may not be correlated. The first is identification of the communication modality (voice, tactile etc.) and the second is command execution in the selected medium. The act of communicating -- speech, tactile or some other medium -- must be designed to be easily learned, consistently repeatable under both

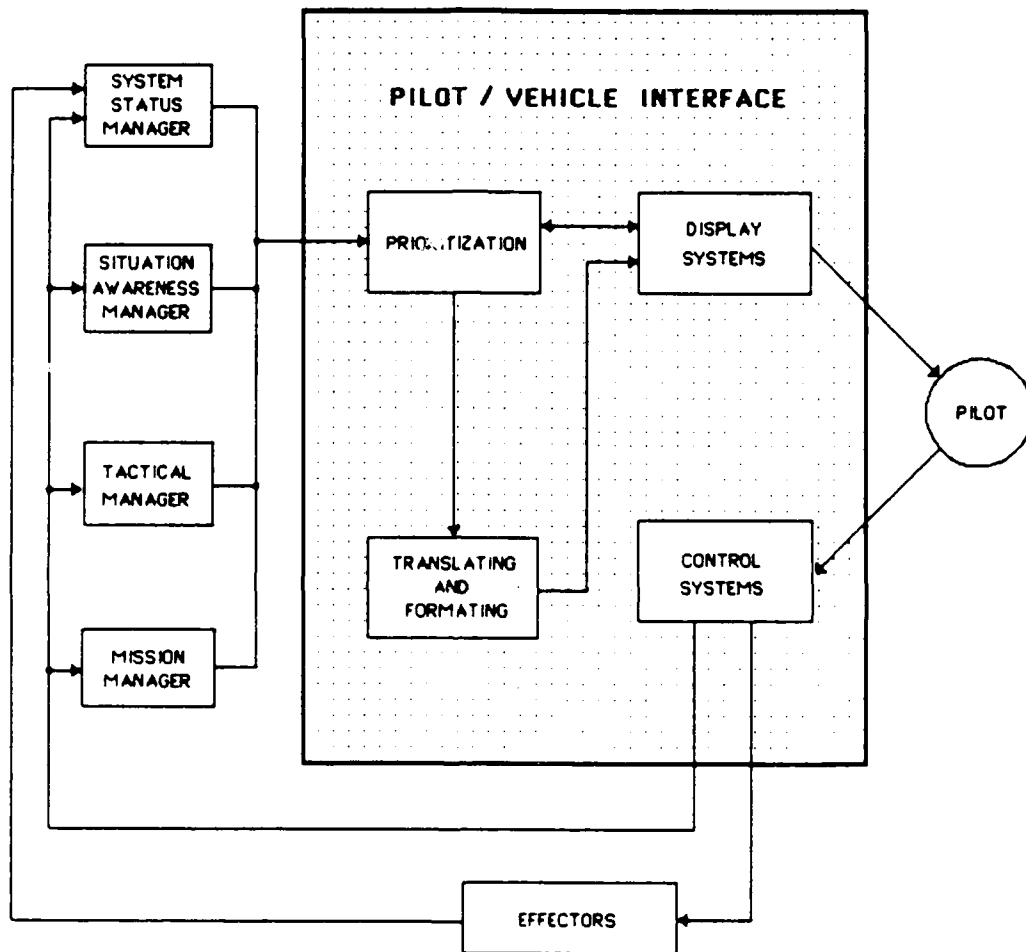


Figure 23 Pilot/Vehicle Interface Block Diagram

physical and emotional stress and recognizably similar when used by all pilots.

In addition to communication with the Pilot's Associate, the pilot must also be able to access many (if not all) effectors directly for emergency and/or backup reasons. The communication media used for this access should be similar to, identical if possible, the media used for equivalent communication between the pilot and the Pilot's Associate.

SECTION 5

AI TECHNOLOGY ASSESSMENT AND APPLICATION

5.1 AI TECHNOLOGY ASSESSMENT

5.1.1 Software

Selection of a robust architecture will allow use of almost all forms of AI regardless of maturity. However, effectiveness of the AI will be related to its maturity as well as to selection of the most apropos technology for a given application. As noted earlier, one advantage of a robust architecture is that it will accommodate improvements in technology in an application - even transitions from one technology to another - without requiring major changes in the architecture.

In today's world of AI technology, the major emphasis is on development of expert systems, vision, and natural language understanding. Continued progress is being made in voice synthesis and recognition, but without the emphasis of the first three areas. As in most new technical disciplines, with increased interest and investment in the field, and with new interest in potential applications for the technology, there is a strong tendency for the technology to lose its early focused drive and "blossom" into real and synthetic divisions of the art. This provides some new insight from diversification but at a great sacrifice in momentum of the principle thrust. This is particularly true in new areas where really gifted and experienced talent is at a premium as is the case for AI.

Because of the large number of papers and other publications in the field, many of questionable value, it is difficult to make a precise estimate of the state-of-the-art or to know if there even a consensus on its status. From recent statements by some of the giants in the field, there seems to be a trend toward honest realism for the potential of today's research, and a retrenchment of prior optimism for expert systems to more conservative predictions for the future. There has begun a gentle shift away from strong reliance on the expert system as the solution for all complex problems formerly left for the human to solve. This stems from two principle considerations in our opinion.

First, there are very practical reasons for the difficulties being encountered in expanding the capabilities of expert systems and, second, there are many more areas where advances in non-cognitive technology can benefit mankind <9> and new insights are being gained in these areas every day. We believe it is not unreasonable to say that in five years, advances in perceptual modes of intelligence will be as significant as those over the past 30 years of cognitive system research.

<9>. Not just in the military.

Limitations of expert systems derive from the fact that they are only emulators of intelligence and not intelligent in themselves. As such, their creators must strive to maintain a high degree of perfection in them as they cannot "recover" from mistakes as can truly intelligent systems. This places a burden on the practical size of such computer programs, for LISP and other list oriented languages are no easier to write error free than any other language.

The second limitation derives from the very serial nature of cognitive processes which expert systems emulate. Attempts to adapt these processes to highly parallel processing architecture, and ultimately parallel hardware processors, is counter intuitive and can lead to even greater inefficiencies if pushed too far in this direction.

Some other limitations are suspiciously man made. It is generally a well accepted fact that today's state-of-the-art in expert systems is best confined to limited (i.e., singular) knowledge domains. When multiple domains are encountered, for the time being at least, they are treated by techniques now being developed for "cooperating" individual experts. There is merit to this approach as the size of larger multi-domain systems suffer from the problems discussed above. However, the partitioning of knowledge domains into different regions is along classic lines. The ability to link data in knowledge systems, whether through semantic nets, frames and slots, scripts, or combinations of these and other techniques is predicated on an underlying association developed through classes of objects defined for convenience of the human cognitive processor. This may not be the best method for intelligence emulators.

While most AI activity has focused on emulation of the cognitive process for problem solving, since this is the thing humans do best, it would seem that more progress can be made in supporting pilots through encouraging present embryonic efforts in perceptual processing. After all, we spend years training cognition out of pilots -- why not build it into the system in the first place.

The preceding arguments should not be taken as a denouncement of expert systems, or a belittlement of their potential contribution to helping solve many of the detail problems to be encountered in developing the Pilot's Associate. Conversely, the discussion is an attempt to: a) place the role of expert systems in perspective and, b) to encourage intelligent assessment of proper versus improper application opportunities for them. In addition, we wanted to shed light on other technologies that singly or, more realistically, in combination with expert systems can have substantial payoffs.

5.1.2 Hardware

Applicable hardware for the Pilot's Associate program includes the current class of general purpose computers, von Neumann and others, and special purpose processors such as those developed expressly for speech synthesis. This section will address only the very large class of general purpose processors within the class of machines applicable to intelligent information processing.

The DARPA is sponsoring research in a number of areas, namely;

- 1) Butterfly Multiprocessor (TM) parallel processing machines under development by Bolt Beranek And Newman Inc., Cambridge, Massachusetts
- 2) Connection Machine (TM) a fined-grain parallel processor under development by Thinking Machines Corporation, Cambridge, Massachusetts
- 3) Programmable Systolic Arrays (WARP) by Carnegie-Mellon University, Pittsburgh, Pennsylvania
- 4) Tree Machines being developed by Columbia University, New York, N.Y.
- 5) Compact Lisp Machines by Texas Instruments Inc., Dallas, Texas

In addition, other major hardware projects are under development with end products of potential value to the Pilot's Associate. These include

- a) Reconfigurable parallel processor architectures controlled through external switches - University of Washington, Seattle, Washington
- b) Lattice arrays of complex processors with low intra-array connectivity - Schlumberger Palo Alto Research, Palo Alto, California
- c) COSMIC CUBE, a multi-node array based on n-cube connection networks - California Institute of Technology, Pasadena, California
- d) The CEDAR Machine, a multi-cluster arrangement of processors under control of a Global Control Unit - University of Illinois, Urbana-Champaign, Illinois

These projects involve techniques to combine individual processors into larger groups or networks in ways designed to enhance simultaneous parallel operation with maximum utilization of resources and maximum speed. Speed comes from basic chip technology and from techniques for inter-processor data coupling. Flexibility is derived from methods of processor control and ability for rapid reconfiguration. Some machines are single instruction multiple data (SIMD) devices and others are of the multiple instruction multiple data variety, while still others can be either depending of configuration. We are not aware of any new developments in multiple instruction single data machines. These could prove very useful in the very early stages of data processing. No system is successful at achieving all ideal goals, but each has its own peculiar advantages and drawbacks.

In many cases, prototypes of these machines have been built and demonstrated. Overall, usable machines are scheduled for availability in time for use, at least at the laboratory or demonstration level, by the Pilot's Associate Program's out years. Some machines may have practical limits as to their scalability from prototype levels to operationally useful sizes. However, in some applications the technology may prove extremely useful even on a smaller scale.

The question that cannot be answered now is whether or not there will be a good match between software requirements and hardware. Now the hardware is being developed in parallel with the software technology. But expert systems are not the only user for these new parallel machines. Many deterministic algorithms can benefit from high degrees of parallelism, particularly where knowledge base data are stored in algorithm form, or high speed true parallel processing is required for generation of multiple options.

5.2 AI TECHNOLOGY APPLICATIONS

The key to effective selection of AI technology for a given application is recognition of the need to carefully evaluate the match between technology advantages and limitations on one hand, and application constraints in terms of symbolic intensity and data processing bandwidth on the other. One should not be surprised to find that the best application is often a mix of technologies.

Since the objective of AI is to emulate human intelligence as the ideal model, an assessment of the types of information processing the human uses in certain circumstances is in order. At the extremes, the human uses cognitive techniques rooted in linguistics to "solve" complex problems. Here complexity is characterized by a need for broad adaptability in a diverse knowledge situation. It encompasses the commonly used terms of "abstraction," "creativity," and "reasoning," and is totally unstructured.

At the other extreme "perceptual" data processing operates in ways obscured from the cognitive to 'solve' more highly structured problems - particularly those requiring reflexive action. Not surprisingly, the latter depends on a more highly refined, in terms of processing efficiency, processes developed over millions of years. Cognitive processing, while more sophisticated and powerful in concept, is considerably newer and not nearly as efficient. Hence, most of the information processing a human depends on to exist is perceptual. <10> And whenever possible the human will convert a cognitive process to perceptual through learning <11> because of its efficiency which, in part, derives from strong reliance on parallel process execution.

<10>. But for survival and growth, he depends on the unique cognitive capabilities developed exclusively to such a high degree in Homo sapiens.

<11>. Training in a more formal sense

One should not conclude that there is some direct relationship between perceptual and cognitive processing closely isomorphic to the sequence of data/information processing stages discussed in Section 2.3. It is not that simple. We use cognitive processes to solve very "simple" problems if they are new to us.

Learning to ride a bicycle or drive a car are common examples. Eventually both of these skills are relegated to the perceptual/reflexive domain. On the other hand, the same case can be made for very complex skills. Beginning chess players rely almost exclusively on cognition. But, after years of playing (training) the skills are considered to reside in the perceptual domain. Is this to say of humans what has been said of computer programs? That once they learn to play the game, it is no longer considered intelligent? Do we get dumber as we learn? Obviously quite the contrary. Perceptual processes can reflect extremely high levels of intelligence. For example, Dr. Norbert Weiner "solved" complex tensor calculus problems routinely through perceptual processes. An accomplishment many "bright" people will never accomplish with either class of processing.

The analogy to combat systems should be obvious and similar if not identical. Unfortunately, we do not currently possess the necessary technology to fully exploit the advantages of perceptual processing, thus we are tempted to use the more mature, but restricted, cognitive processing embodied in expert system technology.

SECTION 6

EVALUATION CRITERIA

There are at least two measures appropo for evaluation criterion of the impact of incorporating AI directly into combat systems. These are measures of performance and effectiveness. Each are addressed in the following sections.

6.1 MEASURES OF EFFECTIVENESS (MOE)

In casual usage, performance and effectiveness are frequently taken as synonymous or nearly so, however they are not and, for the Pilot's Associate, we must carefully distinguish the two and define separate measures for each.

Effectiveness relates to objectives; performance to mechanics/specifications. We define effectiveness as how well a system achieves its objectives. And we define performance as how well a system performs "mechanically," especially vis-a-vis its specifications. As a consequence, measures of effectiveness are naturally statistical in nature and measures of performance, by definition, are deterministic. To be useful, both must be measureable by some realistic means - for example, to set "To win the war" as a goal for a specific system is not realistic as it is not readily determined by any practical means. More realistically speed, range, and climb rate are typical measures of an aircraft's performance. Its effectiveness is typically measured in terms of numbers of planes killed, bridges destroyed, etc. per sortie.

Since goal-directed activities tend to hierarchical arrangements, objectives and associated effectiveness measures are also hierarchical. For example, a military organization may choose to deter war by threatening to win it. While valid, such goals are too remote and vague to allow even workable definitions of effectiveness, much less measurement of it. The value of the top goal lies rather in its summit position which allows us to infer a supporting pyramid of definable and eventually measurable sub-goals and objectives such as:

- * War - win the war
- * Campaign - gain/maintain regional air superiority
- * Battle - intercept escorted strike
- * Engagement - kill enemy aircraft and survive.

Each level of this objective hierarchy consists of several entities from the level below and low levels involve fewer participants. Only at the lower levels can we begin to define useful measures of effectiveness. For example, at the battle level, a reasonable measure of fighter effectiveness might be the number of enemy strike airplanes "leaking" through the fighter defenses (CAP and Scramble) into area and point SAM defenses. Whereas, an engagement of a few coordinated Blues (a "wave" of interceptors of section to squadron size) against a portion of a large incoming escorted strike could use number of Red kills and Blue losses as MOE's.

Below the engagement level, no new objectives emerge, so no new basic MOE's are defined (that is, clearly related upward into the objective hierarchy). Rather, system and subsystem performance issues become important (e.g., airplane performance, sensor performance, fire control system performance, weapon performance, and ID performance). Thus basic MOE's applicable to evaluating an enhanced combat system reside at the engagement level. Furthermore, their measurement is usually determined through simulation using either Expected Value or Monte Carlo techniques. Typical questions asked in establishing meaningful MOE's at this level are:

- 1) Does the presence of AI substantially enhance Blue effectiveness? Can it be measured?
- 2) If demonstrable, how do various levels and types of AI contribute to effectiveness?
- 3) How does system effectiveness vary versus performance of those subsystems using AI?

For example, in an air-to-air engagement several measures of effectiveness can be defined:

- * number of Red aircraft killed
- * number of Blue aircraft killed
- * number of Neutral aircraft killed
- * total launch opportunities of Blues
- * Blue launch opportunities lost due to lacking ID
- * total Blue launches
- * Red launch opportunities avoided due to ID
- * total Red launches
- * exchange ratio
- * figure of merit of Blue launches
- * figure of merit of Red launches

The first two of these suggested MOE's are considered basic measures as they relate upward in the effectiveness hierarchy. The remaining items are considered supporting measures which relate downward to the subsystem level. However, all of these are independent and as such are of little value alone in testing the basic hypothesis of the impact of AI on system effectiveness. Therefore, more meaningful measures are ratios of each MOE value for the concept under test compared to some baseline system MOE value.

Supporting MOE's are useful for getting a handle on cause/effect relationships and on-going assessment of the usefulness and consistency of results. As above, ratios of these supporting MOE's are useful to show relative effectiveness for various AI application modes and performance levels. However, the basic MOE's, Blues lost (L) and Reds killed (K), are the components needed for effectiveness decision making.

To this point we have defined: (1) the terms effectiveness and performance as we use them, (2) the appropriate hierarchical level at which measurements are most meaningful--engagement, (3) suggested basic and supporting MOE's at the engagement level, and (4) the need for MOE

ratios in testing the basic hypothesis. We will next address aggregation, combination, and weighing of MOE's and define one more measurement level -- adjunct MOE's.

One aspect of arriving at overall measurements of effectiveness is aggregation of individual measurements over a range of parameters such as scenarios, pilots, AI technologies, etc. The first level of aggregation is over a number of test runs of the same (essentially) conditions to obtain statistical significance. Inherent in this level of aggregation is the assumption each trial is statistically independent and all measure (MOE's principally) are of equal importance (i.e., weight). However, aggregation of results over scenarios, for example, by definition implies different values associated with each measurement; otherwise all runs could be made using only one scenario. Therefore, weighing values must be applied to MOE's when aggregating over levels where values are not uniform.

While the basic MOE's and supporting MOE's are all useful evaluation tools, it is necessary to provide a single measure that summarizes the overall evaluation for use by decision makers. Neither the single measure or the separate measures are sufficient by themselves, but together form the necessary hierarchy of evaluation results the decision makers need. One obvious choice for an overall measure is a weighted linear combination of Reds killed (K) and Blue losses (L) as:

$$E = aK - bL ; \text{ with } a, b, \text{ positive.}$$

The weights "a" and "b" clearly depend on mission, theater, battle status, etc.; so effectiveness pertains to a specific context or scenario with stated mission objectives on the part of both (all) parties.

Now, for MOE weights for aggregation and combination purposes, the question of who assigns the weights is obviously critical to the evaluation results' meaning. Values should be selected based on experience and inputs from appropriate Air Force personnel. These values should then be adjusted, as necessary, in consort with the Air Force and/or other military personnel.

Before leaving MOE's we note that the basic MOE's, K and L, can be subdivided into adjunct MOE's, at least in some scenarios, for the purpose of answering the question "why." Reds killed might be composed of Red bombers killed (Kb) and Red fighters killed (Kf) for scenarios involving both Red types. In such cases, summing only total Reds killed as an MOE amounts to weighing the importance of killing bombers and fighters equally, that is choosing $c = d = 1$ in:

$$K' = cKb + dKf .$$

This seems an unlikely result in all cases, so "c" and "d" should be handled as "a" and "b" above. Then weighted Reds killed (K') becomes the appropriate MOE with Kb and Kf helping to explain K'.

Consider another adjunct MOE. For L, we have Blue losses due to Red action, L_r , and those due to (inadvertent) Blue action, L_b . Since good AI should help reduce fratricide, looking at L_b separately might give insight into AI effectiveness. Of course, if $L_b \ll L_r$ even with current (baseline) approaches, this MOE won't mean much. Another benefit of good AI performance would be to help the pilot avoid threats. L_r would help isolate this aspect of effectiveness. Since a Blue airplane lost is just as costly whatever the cause (Red action, fratricide, accident), a "weighted" loss is not needed, so $L = L_r + L_b$ is a suitable MOE.

6.2 MEASURES OF PERFORMANCE

Turning to measures of performance (MOP's) we find a conceptually simpler picture. Typical MOP's might be the number of threats correctly and/or completely described, time to establish new plans or new tactical options, ability to convey complex information with minimum error in required time window, etc.

These MOP's are necessarily rather gross. We cannot expect to relate effectiveness to micro-performance (e.g., signal processing bandwidth of a particular sensor) since variation in micro-performance simply won't show up in engagement results. Only macro-performance parameters can reasonably be expected to exert measurable effect on MOE's. This means simulating already designed candidate(s) at the micro level, measuring both macro performance and effectiveness and inferring relationship between MOE's and MOP's. Of course, once inferred, these relationships can be used for further performance requirements and sensitivity analyses if desired. These help in making R & D resource allocation decisions, especially if requirements should exceed current feasibility. And they provide inputs to further technology refinement efforts.

It's because candidate AI concepts and approaches (or minor variations thereof) are to be evaluated rather than an analysis of effectiveness versus parametrically varied macro-performance that relative effectiveness was emphasized earlier. In particular, at least one baseline combat system is required to normalize against.

We also expect relativity in MOP's to be important. Some MOP's are absolute in the sense that they refer explicitly to performance of only one process or subsystem making up the weapon system. Other MOP's, for example, relate primarily to weapon performance and others relate to fire control system performance insofar as it supports the weapons. These relative MOP's reflect most closely the underlying structure of effectiveness.

Weapon system effectiveness depends in a complex fashion on the (macro) performance of all major processes. The danger in evaluation is that performance of other processors might mask, totally or partially, the effectiveness contribution of one processor. An even more significant potential masking problem is the fact that demonstration/testing will involve pilots-in-the-loop making real-time tactical decisions. Past experience in, for example, the ACEVAL/AIMVAL

program has shown tactical variation and learning to be far and away the most serious source of masking. Once again we face the need to compromise between realism and masking. These issues are subject for more detail study.

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APPENDIX A

GLOSSARY

TERM	DEFINITION
afferent display	Display system having the requirement and capability to redirect the observer's attention from other matters to itself and also to redirect attention within itself.
aircraft	Any man-made heavier- or lighter-than-air vehicle, powered or unpowered, capable of sustained flight. Includes airplanes, gliders, blimps, etc. Often confused in usage with "airplane".
airframe	Main structural part of aircraft, including skin if skin is a structural member. Also includes control surfaces but not actuators.
analytic	Having the characteristics of any process that attempts to describe, explain or understand a phenomenon by breaking it down into simpler or better understood constituents.
analytic solution	The second stage in problem solution - following problem definition. Synthesized from functional requirements, it is manifest as a set of performance requirements as input to the third stage, mechanization.
architecture	Explicit relationships among elements of a system. May be at different levels for any system (particularly information processing systems) including functional, process, and formal. Collectively known as system architecture. Term "architecture" connotes less tangible aspects of "structure."
artificial intelligence	Intelligence attributed to man made systems. Also refers to part of computer science concerned with symbolic inference by computer and symbolic knowledge representation used in making inferences. c.f intelligence, machine intelligence.
automation	Operation in accordance with prescribed rules without human intervention.

TERM	DEFINITION
avionics	Branch of engineering/industry that applies electronics technology to problems and requirements of aviation. Also refers to that industry's products.
battle	A series of engagements by one or more participants or groups of participants designed to achieve a minor tactical objective. Characterized by durations usually measured in a few days.
blackboard model	A model whereby system elements communicate with each other by means of a common data storage called the blackboard. When any one element writes to the blackboard, all elements read and those with interest react.
bottom up	Proceeding from most elementary or lowest-level components of a system to those of higher level or complexity.
campaign	A series of battles designed to achieve a high-level tactical objective. Characterized by durations measured in weeks or months.
captain	As in the Naval Ship paradigm, the highest-ranking member of a crew in terms of control over system behavior.
characteristic	As related to weapon systems, a non-statistical physical measure of a system or any of its components. Examples are height, weight, color, etc.
closed-loop problem	One whose solution depends on the ability of the system to influence its input.
cockpit	The physical space bounding the crew in the airframe. Includes all non-structural devices constituting that boundary, i.e., CRT faces as well as floor panels. In summary, it is the formal crew/machine interface.
cockpit automation	Automating some or all of the crew/system.
code	Symbolic representation of information according to some prescribed scheme. May be unique as is the case of musical notation, or ambiguous as in natural languages.

TERM	DEFINITION
combat	An attempt to resolve differences by coercion or force.
computer	A device that manipulates or processes symbolic information according to some prescribed instructions, in accordance with established rules.
controls	Those devices directly (physically) interacting with the crew as the first step in carrying out some action or command, e.g., a switch, knob, microphone, etc.
crew	The human complement of an aircraft.
crew/system	The sum of crew and that part of the aircraft required only because of the crew's presence.
current situation model	An internal model of the world of interest at the current instant of time consisting of both physical and intentional quanta.
data	Quantitative or qualitative results of observation, specification, intuition, etc. in their original form before they are irreversibly processed by or for the system of reference.
data processing	Irreversible manipulation of data with the specific objective of increasing its information content or convenience - the creation of symbolic information at the expense of original data.
decision	Choice of or among available alternatives.
decision aid	information generated to assist humans in decision making including alternative courses of action and measures of relative or absolute utility associated with options.
display	Device for conveying data or information or both to the crew. In this usage it is not limited to visual context.

TERM	DEFINITION
dual command	The concept of a tandem upper-tier command structure. The higher position (pilot, captain, boss, etc.) generally concentrates on interfacing with the outside world while the second-in-command generally looks inward and down to the rest of the organization. Both serve as strong crosscheck on the other to avoid catastrophic failures.
effectiveness	Relating to the degree an organization (human or otherwise) achieves its goals in accordance with established criteria, generally construed to be quantitatively related to its organization, application, and to some extent, its formal state of the art.
effector	The last device(s) in an open or closed loop system to interact with the external environment.
emulate	To strive to equal the end result or effect of a process without necessarily duplicating the process itself.
engagement	A single combat experience (with one or more opponents) from initial encounter through disengagement. Characterized by durations measured in minutes or hours.
executive	The second highest ranking role in the dual command structure. Known as the "Officer-of-the-Deck (OD)" in the Naval Ship Paradigm.
function	Description of a system's interaction with its environment as viewed from outside the system.
future situation model	An internal model of the world of interest at some future instant of time consisting of both physical and intentional quanta.
goal	The highest level of desire, invariably qualitative in nature and not necessarily singular in instance.
heterostasis	Condition in which a given variable is maintained at its maximal level.

TERM	DEFINITION
heterostat	Device which seeks a maximum of some input or state.
hierarchy	An ordering by rank along some dimension such as authority or levels of abstraction.
homeostasis	Condition in which all critical variables are kept within acceptable ranges.
homunculus	Literally a little human (man). Also a model (physical) of a human. In a testing context, using human intelligence (possibly attenuated) to emulate machine intelligence for evaluation purposes. Also, in intelligence theory, a closed loop approach acting as a command generator, reader, and interpreter or any similar information processing role. cf. Information Processing Module
human engineering	Pertaining to analytic representation of humans including their needs and capabilities.
information	Symbolic--any data possessing meaning relative to objectives under consideration. (Not to be confused with Shannon or thermodynamic information.)
information processing	Reduction, storage, retrieval, compilation, refinement, etc., of information.
information processing module	Terminology coined by David Marr (MIT) for a discrete process within an information processing system hierarchy. Similar to a computer task. cf. homunculus.
integrate	To combine like and/or unlike elements (rules, functions, hardware, etc.) into a useful whole. Does not necessarily connote optimization, synergism or intelligence.
intelligence	In an information processing system, the difference in effectiveness between the whole and the sum of its parts.
intent/purpose driven	Commanded at the symbolic level.
intentional system	One exhibiting highly focused behavior associated with known goals and objectives.

TERM	DEFINITION
machine intelligence	Intelligent behavior exhibited by a machine. cf. intelligence.
man/machine	Implying joint participation of man and machine(s) as a prerequisite for operation.
mechanization	Translation (from analytic solution) to formal structure. The third stage in the process of problem solution.
meta-paradigm	Higher-level paradigm, i.e. one that subsumes a class of lower-level paradigms.
metrics	Quantitative criteria.
minimal information	Least amount of information required by a process (human or machine) to permit operation in conformance with expectations.
mission	A specific combination of goals, objectives, and rules.
model	A hard, soft, or conceptual structure created or adopted to represent a certain segment of reality.
naval ship paradigm	Model of a command system represented by that used aboard naval ships. Includes concepts of dual command structure, ship's condition, and standing orders.
objective	Quantitative state toward which a system or process strives. Usually required to achieve goals.
open-loop problem	One whose solution (if solvable) may not influence the input.
paradigm	Particular system taken as model to illustrate essential characteristics of a class of systems or theories.
perception	A single unified awareness derived by adjusting an internal world model of interest to be compatible with sensory processes and existing beliefs.

TERM	DEFINITION
performance	The act of a process accomplishing a function. cf. function.
pilot	The highest ranking member of an aircraft crew, comparable to the captain of a ship in the navy.
problem definition	The first stage in a formal procedure for effecting a problem solution. Requires as output a specification defining the solution's interaction with its environment (functional specification) and the criteria against which the final solution will be validated.
process	A systematic series of actions directed to some end.
recursion	Nesting of some process element successively within itself.
resource	Any entity possessing utility as means for some desired objective.
rule based	(Process or program) governed by or utilizing a prescribed set of rules deriving from external knowledge sources.
scenario	Hypothetical set of related circumstances and/or events - also an instance of a mission.
single combat warrior	Entity that engages in combat with another single entity under autonomous conditions in lieu of combat between groups (e.g. armies).
ship condition	Specific state of ship's readiness for combat.
sign	A token indicating relative position of a quantum with respect to a reference.
signal	Direct analogue of remotely sensed property of external entity.
signal processing	Reversible manipulation of raw sensed data before detection. Usually high bandwidth.
simulate	To imitate the behavior of a process by direct representation.

TERM	DEFINITION
situation awareness	A perceptual gestalt of the physical and kinetic world of immediate interest as represented by an internal current situation model(s).
slideback	Technique of finding value of unknown quantity by varying value of known quantity in a bridge or balance circuit (comparison).
standing orders	Set of instructions or commands for a system that take effect automatically under a prescribed set of conditions (stimulus).
stimulus	Any signal received by a system capable of eliciting some response by the system.
strategy	Overall plan or combination of tactics to be used in achieving a goal.
structure	Set of all tangible relations among the elements of a system.
subsystem	Any subset of system elements capable of functioning as or constituting a system.
successive refinement	The act of developing a detailed description (of a process, for example) by expanding a high level description in successive stages, each simpler in some way than the last until reaching some ground case.
symbol	Any piece of information consistently representing some other entity.
symbiosis	The mutually beneficial association of two dissimilar functional entities
symbot	An intelligent but non-autonomous machine requiring close interaction with a human to function, = symbiosis + robot
system	Any collection of related elements operating in conjunction to produce a desired effect or achieve a desired goal or objective.

TERM	DEFINITION
system synthesis	Art and science of combining technologies and/or their products with philosophical, analytical, and architectural disciplines to achieve a specified goal and associated objectives. Primary mechanism at work during analytic solution and mechanization stages of problem solution process.
tactic	Particular maneuver or operation designed to accomplish some particular limited objective.
tactical awareness	A cognitive gestalt of the implications of the physical and kinetic future world of immediate interest as represented by an internal future situation model(s).
tangled hierarchy	Term coined by Douglas R. Hofstadter referring to highly interrelated n-dimensional process systems - specifically systems exhibiting a high degree of intelligence.
technology	Highly focused body of knowledge dealing with the development, construction, and use of tangible objects.
top down	Proceeding from most complex, sophisticated or highest levels to those of less complexity or lower level. An example external to a system is the reduction of its role or mission to its constituent functions. Internal to a system, it is the development of the process substrate through successive refinement of its highest level process description.
utility	Measure of usefulness or degree to which an entity can satisfy requirements. Most often used as measure of effectiveness in econometric terms (its source).
validation	Act of establishing the degree of compliance of a system with its effectiveness criteria.
verification	Act of establishing the degree of compliance of a system with its performance criteria.
weapon system	Any system (including man as necessary) designed to be used in attacking or defending in combat.

TERM	DEFINITION
workload	Instantaneous sum total of motor and cognitive demands on an operator (crew member) in performance of assigned duties.

APPENDIX B

AIR-TO-AIR MISSION DESCRIPTIONS

Air-to-air combat engagements can be roughly broken down into two categories: 1) longer range, forward hemisphere engagements, and 2) shorter range, maneuvering or dogfighting engagements. The latter typically involve relatively few combatants on each side and the employment of infrared missiles and guns, while the former are characterized by greater numbers of participants and weapons requiring the launch aircraft's support for some portion of the flight. The demands on the pilot and the air combat system may vary dramatically during these two types of engagement and the PA may be able to contribute at different levels. However, the differences among original missions (and among the resultant demands on the air combat system) largely disappear once a dogfight is entered. Therefore, the aspects of missions that apply beyond visual range (BVR) will be examined here and the visual air-to-air engagement will be treated as a separate mission.

Most air-to-air missions are planned to be flown with at least two friendlies operating as a team, often with ground support. The PA must be able to support cooperative operations while still being fully capable of autonomous operation. Autonomous operations place demands on the system that differ from those of cooperative operations. In autonomous operation a critical need is to obtain information because there is only one source of situation awareness--the ownship. In cooperative operations, the prime difficulty may be in sorting out the more voluminous data available, choosing a best source or combination of sources of data and mixing it with ownship data. The air-to-air mission descriptions have focused on autonomous operation (although communication with other friendlies via JTIDS or other means is included in the later task analysis).

Review of references 1 through 5 led to the selection of five particular air-to-air missions: CAP defense of an AWACS, defensive counter air, ground-launched cruise missile defense, offensive fighter sweep, and strike escort. These five represent a consensus of the missions described in references 1-5 and, with relatively minor changes, have general applicability for both the Air Force and Navy. Because of the nature of the PA program, most of the mission descriptions will focus on Air Force applications. All missions will be described for a 1995 time frame.

B.1 AWACS DEFENSE

The AWACS is a cornerstone of the allied command and control system for air space control in Central Europe and in other theaters as well. This element provides commanders with one source of the big picture from which they can make informed decisions on resource allocation. The Soviets recognize that the weak link in any defense system is communications, and their predicted response will be to create a heavily jammed environment and to eliminate the AWACS as early in a battle as possible.

air combat is entered. Sensor volumetric coverage is quite small at close ranges and does not cover enough of the battle area to provide adequate situation awareness. As a result, much of the battle is fought with the pilot's head "out of the cockpit". This means that he can't be looking at the controls and displays that are necessary for sensor management. Furthermore, the angular geometry changes so fast at visual range that there is probably insufficient time to direct the sensors in many situations. Clearly, improvements in the way sensors can be managed at short ranges might have a large payoff in system effectiveness.

Another critical area is the reaction of the NATO fighter to an inbound enemy weapon. Options include the use of dynamic maneuvers or the use of countermeasures. Each can be effective if the right choice to defeat the threat is made in a timely manner. Not all threat-defeating actions work equally well against all types of threat. For instance, use of a flare against a radar missile would be quite futile. Similarly, the choice of when to execute the action is critical. An end-game target maneuver may prove useless if executed too early (giving the missile time to react) or too late (no reaction by the missile required). Currently, the decision on the use of evasive action, either maneuvers or countermeasures, is totally at the discretion of the pilot and normally occurs at a time when there are many demands on his attention.

start to diminish. As the quality or number of predictions decreases, it is likely that the fighter will be less successful in the engagement. It should be noted that any plan must be flexible and adaptable to change, as nothing in air-to-air engagements is static. Indeed, the ability to react to sudden shifts in conditions is crucial to winning an air-to-air engagement.

Once the plan is conceived, it must be executed. This begins with the maneuvering of the aircraft into the position desired for starting the actual battle. This means first achieving the desired speed, altitude, and position relative to the threat. As the transition is made from current conditions to the desired ones, the fighter must be constantly alert for changes in the target status-- heading, speed, sensor status (radiating or not), use of EW, etc. Since multiple target attacks are so time-critical, a basic goal of the NATO fighter will be to slow down the pace of events--if possible, turn the multiple target engagement into a series of single target engagements, or at least separate the time periods during which the fighter is within the lethal range of each of the threats. This requires that some knowledge of the lethal radius can be provided by the air combat system. Indeed, this may be a crucial element in survival.

As the desired conditions are reached, the pilot will have to continually replan his attack. The decision of whether and when to fire is obviously crucial to success and survival--a mistake in timing in either direction can be quite literally deadly. For weapons postulated for 1995, the decision of when to stop illumination of the target for weapon guidance will be critical to survival. As long as illumination is required, the fighter is limited in his ability to maneuver without losing the missile, and this makes him quite vulnerable to attack by other targets. There will be times when a fighter may choose to break off an attack (and give up a missile in flight) if the situation becomes too threatening. The decision whether to "hang in there" or exit the arena is obviously critical to survival and to success in killing the enemy fighter. All of the decisions noted here occur in a very short time frame and are critically dependent on fast action with somewhat limited data upon which to base them.

As noted earlier, most losses in a multiple target arena are due to targets the fighter never realized were threatening him. The reason for this may be either that the target was not sensed by the avionics, that the pilot made a mistake in his assessment of the threat, or that he was simply too preoccupied with other tasks to recognize the danger. Under current conditions, even when the pilot senses a threatening target, there is limited information reflecting the level of the threat it presents--the pilot must depend on "rules of thumb" that are by their very nature rather generic and simplistic. Information regarding an enemy's launch capability, his likely tactics, the zone of no escape from his weapons, relative shot "sweetness" and the like could greatly affect the battle plan of the NATO fighter and increase his chances of survival.

As the battle evolves, the combatants will come within visual range, and the way the battle is fought will change again. References 6 through 10 have demonstrated that sensors begin to lose value as visual

other missions (see section B.6). In the TARCAP role, the escorts take up patterned flight over the strike area. As in BARCAP, the pattern is maintained until threats are detected. The enemy forces are engaged by a portion of the TARCAP aircraft, preferably before they become a threat to the strike group. As in BARCAP, the key element is early detection and assessment of the threats.

After the mission over the target area is completed, the strike group must reform with the escorts for the egress. The functions required of the escorts here are essentially identical to those during penetration.

B.6 AIR-TO-AIR ENGAGEMENT

Many of the missions described earlier ultimately result in an air-to-air engagement between a group of NATO fighters and a group of WPN fighters. For purposes of the description of the functions required in such an engagement, we shall consider only the requirements on a single NATO fighter, who may have to coordinate action with a wingman. The manner in which the air-to-air engagement was entered does not drastically affect the required functions of the air combat system as long as fuel and ordnance supplies are adequate. Therefore, the description in this section will largely ignore the question of how the engagement was entered.

For the air-to-air engagement under consideration, rough parity in capability between the NATO and WPN fighters is assumed. This results in the most difficult requirements being placed on the air combat system (as compared to a distinct NATO advantage in capability). In most scenarios, the NATO forces are expected to be outnumbered in the ratio of three or four to one or worse. There will possibly be several types of WPN fighters, with different performance, sensor, and ordnance capabilities. All of the enemy fighters will pose a deadly threat to the NATO fighters.

The engagement is begun when a NATO fighter decides to intercept the WPN fighters. As noted earlier, this point could be reached in a number of different missions--AWACS defense, Defensive Counter Air, Offensive Fighter Sweep, and Strike Escort. The timing of the decision to intercept will affect the time available to complete certain tasks within the engagement itself. Assuming the threats are in a track file when the engagement begins, the first step is to plan the battle. Issues here include the questions of which targets are most threatening to ownship, which targets are in a position most vulnerable to attack (Is ownship above or below a target? Is it currently in range?

etc.), which targets will be vulnerable in the future, what is the likely response of targets that are attacked, and others. Most of these issues involve not just observing current conditions but predicting future events or reactions. The correctness of the predictions will directly influence the success of the engagement. Most prediction in today's fighters is a function of the pilot's capabilities and the time available. As the fighting environment becomes more complex, with more sophisticated jamming and a greater numbers of threats, the pilot's ability to predict accurately issues such as those described above may

designed to minimize interactions with SAM sites and zones and to take advantage of the cleared air corridors provided by the offensive sweep. Once the target area is reached, the threats to the escorts will consist of interceptors attacking the strike group and point defense SAM's and AAA around the target site.

The mission begins with the rendezvous of all the elements that make up the strike force--the bombers, jammers, and escorts. The preplanned formation is entered and the force heads toward the FEBA penetration point. During penetration, it is the job of the escorts to provide air surveillance while maintaining the group flight pattern. One of the keys to mission success will be the coordination of situation awareness by all of the escorts. In all likelihood, no one of the escorts will be capable of complete spherical sensor coverage, so each will be assigned a sector where it is responsible for detections. Some mission descriptions show the escorts shuffling around in position to provide more complete awareness and coverage. Possibilities include a patterned weave around the strike group and a circular permutation, where single escorts periodically move from the front of the formation to the rear, with others moving up in the formation. However it is accomplished, the key element will be early detection and assessment of potential threats and quick reaction to them. If WPN activity is perceived as threatening to the main body of the strike force, some portion of the escorts are vectored out to engage the targets before they can attack the main group. At this point, the actual engagement is similar to that for any number of other missions, with similar demands on the air combat system (see section B.6). After the engagement, the strike group is rejoined if fuel permits. If not, the escort-turned-interceptor returns to home base. The rejoining process (when appropriate) involves planning of the desired route and profile while still remaining on the lookout for more enemy fighters.

As with the offensive sweep, a significant threat to the escorts is presented by the SAM belts near the FEBA. Early warning of their presence will have a large impact on mission success. The penetration of the FEBA is a critical time for the escorts in terms of demands on the system. Their primary attention must be on the air surveillance role in protecting the strike force. However, their survival is also critical, so SAM detection and avoidance cannot be ignored. The penetration period is probably the most demanding on the system of any in the entire mission.

Upon reaching the target area, the escorts assume their role as either BARCAP or TARCAP. In the BARCAP role the fighter flies a pattern at a position between the strike group and the probable origin of defense forces. The aircraft assigned to BARCAP keep intercepting threats as they appear. BARCAP usually ceases when the strike group has completed its mission over the target area. The BARCAP role is essentially one of target detection followed by interception and engagement. Timely reaction to detected threats is vital to protection of the strike group, so the assessment of a potential threat and the decision to attack are critical to the mission's success. Interception must be completed before the threat comes within lethal range of the strike group. Once an engagement is entered, the functions required of the air combat system are quite similar to those for engagements in

Assuming the sweep force survives the air-to-air engagements, the final phase is the retreat across the FEBA, again penetrating the SAM defenses. The SAM belts will have been warned of the sweep's return and will have some portion of their firepower focused in the proper direction in anticipation. Acting in favor of NATO will be some potential confusion in the SAM's capability to identify their targets correctly. The egress across the FEBA has most of the same perils (and therefore required functions) as the ingress.

One possible variant on the offensive sweep mission described might be the reluctance of the WPN fighters to engage the NATO fighters. Rather, they may lie in wait to attack the strike force they believe will soon follow. In this case, the sweep force would have to initiate the battle, locating potential targets, assessing them and engaging them. All of the same functions are still required, with their criticality unaltered. One additional requirement could be for the sweep force to fly a strike-like flight profile in hopes of luring out the WPN fighters.

Another variant of the offensive sweep may be in the mission definition itself. Air wars are often a battle of attrition, with the loser being the side that first runs out of assets or incurs an unacceptable loss rate. A variant of the offensive sweep mission is then one where enemy aircraft are engaged regardless of where they are, with the thought that threats killed today won't threaten tomorrow. In this variant, target ID is critical, to avoid fratricide and to provide a timely attack on any threat. The sweep force is free to wander wherever it feels advantageous engagements might occur. Many of the functions and requirements among the variants of the sweep mission are similar, the only differences being the geographical area of concern and the way the geographic relationship of the threats affects the decision of which ones to attack.

B.5 STRIKE ESCORT

The purpose of the strike escort mission is to provide protection against enemy airborne attacks for friendly strike and support aircraft performing missions that require penetration over the FEBA into enemy held territory. The strike escort mission is accomplished by fighter aircraft accompanying the strike group during the penetration phase and performing target CAP (TARCAP) or barrier CAP (BARCAP) as the strike group approaches the target area. In the TARCAP role, the fighters fly within the area close to the ground target while the strike aircraft carry out their attacks. In the BARCAP mission, fighters establish a barrier between likely approach routes of WPN fighters and friendly penetration/egress routes.

The potential threats and targets for the escorts are very similar to those in the offensive fighter sweep--the SAM belts near and behind the FEBA and the WPN interceptors. The escorts fly the same basic flight profile as the strike group and will therefore be exposed to roughly the same threats. In general, the escorts fly above and to either side of the strike group, with visual surveillance maintained in most cases. The strike group will fly a preprogrammed flight path

forces will send interceptors to engage the NATO attackers. The heavy jamming environment may make communication between sweep members difficult and will degrade ownship sensor performance.

The mission is defined as beginning with the sweep force on the friendly side of the FEBA. The control center detects a group of enemy aircraft operating within the sweep region and assigns them to the sweep force. Alternatively, the sweep force could detect the enemy air activity themselves. Either way, the sweep force heads across the FEBA to engage the enemy fighters. A critical task in this phase of the mission will be selecting the flight path and profile within rather narrow constraints (basically staying within the sweep area while maintaining a satisfactory fighting posture). The selection of flight path and profile is largely driven by SAM avoidance or evasion. However, during the period of transit towards the assigned target package the sweep force could be "jumped" by other enemy fighters at any time. It is possible that some form of defense suppression will have "softened" the SAMs somewhat, making flight path decisions simpler. This will be an extremely busy period for the air combat system. Target track establishment and maintenance is critical to mission success and will demand significant attention. However, of more immediate concern are the SAMs, and their detection, avoidance and evasion must be heavily weighted.

In general, no other friendly activity is expected to be within the sweep area, so target ID will not be difficult--pretty much anything moving and not squawking can be considered hostile. The problem then becomes which targets to engage (in what is probably a target rich environment), when to fire, and how to survive. While survival may not be explicitly specified in defining the mission (which is to clear out a corridor), the large disadvantage in resources of NATO in relation to WPN forces dictates that surviving to fight another day is of supreme importance. Given this importance, situation awareness may be the single item most critical to mission success. As noted earlier, programs such as AIMVAL/ACEVAL, AMRAAM OUE, and MISVAL have demonstrated that the majority of WPN kills in a multiple target arena are accomplished with the NATO aircraft never sensing or seeing his attacker. This implies that sensor management is a critical task for the air combat system. It is only through a coordinated use of all the ship's sensors (including JTIDS or its equivalent) that the fullest understanding of the situation can be reached. The need for constant vigilance on the part of the pilot and system while accomplishing other tasks such as weapon management makes the offensive sweep mission a very difficult and dangerous one.

Much of the success of the mission will depend on the relative capabilities of the NATO hardware and software (weapons, sensors, algorithms, etc.) as compared to those of the WPN fighters. The expected highly jammed environment may drastically hinder sensor performance and negate any technical advantage the NATO forces might have in the clear. Anything that can be done to increase system effectiveness in a heavily jammed environment will have a strong impact on mission success.

sensors are hindered by the small cross section and low flight profile, which ultimately results in a rather small launch window for the interceptor. Avionics and weapons projected for 1995 will probably result in a time interval of less than one minute for the completion of a first pass interception. Most scenarios examined for this mission show the cruise missile attack in stream formation, with spacing of roughly 10-15 seconds. However, this sequential spacing of the targets does not necessarily translate into a sequential engagement by the NATO interceptors. Shot quality, F-pole, kill assessment, and re-attack will compress the launch opportunities into a nearly simultaneous attack on the entire fleet of GLCMs.

Critical functions for the interceptor are target detection and determination of when to fire in order to optimize shot quality while minimizing leakage. The success of this mission is largely dependent on the avionics and weapon capabilities as well as the ability of the pilot (or some other system) to detect a small target in a high-clutter environment. Obviously, there can be no engagement without a detection. Further, previous studies have emphasized the importance of initial launch range in determining the ultimate number of GLCM leakers. Initial launch range can be affected by a short detection range. Given ample detection range, the most critical function is the determination of when to launch.

B.4 OFFENSIVE FIGHTER SWEEP

The offensive fighter sweep is a mission designed to achieve air superiority over a limited area for a limited time. During this time, friendly bombers penetrate the FEBA and attack enemy targets. The area of operation for the sweep is within 65-80 Km of the enemy side of the FEBA. The objective of this mission is to seek out and destroy enemy aircraft that might attack the bomber group which follows. Since the WPN forces are known to use highways and major roads as landing strips, the exact locations of all the potential WPN interceptor points are not known, making long detection range desirable.

During the sweep operation, the NATO aircraft will be in constant contact with the central control for long-range detection support and early warning of threat activity. WPN forces will react as the NATO aircraft approach the FEBA. The sweep force must then survive the SAM belts near the FEBA, where both radar and IR missiles can be expected to be present. The electromagnetic environment will be heavy with radiation from early warning radars, acquisition radars, and all types of jamming equipment.

There are numerous threats in this mission and accordingly the biggest challenge to the air combat system is that of survival. Dense SAM defenses around the FEBA will affect the flight profile used during penetration, both in speed and altitude. However, this same flight profile adopted for SAM avoidance may leave the fighter in a poor flight posture for air-to-air combat. After the SAMs, the principal threats to the fighter will be the targets themselves. In this mission, the sweep force is to seek out enemy fighters and engage them. It is expected that in at least some cases, no seeking will be necessary, as the WPN

For those interceptors assigned to engage the escorts (or for those who happen to encounter an escort while attacking the bombers), the engagement numbers will probably range from 1-on-1 up to few-on-few, beginning at BVR and possibly evolving into an engagement within visual range. Situation awareness is critical here, as most kills in multiple-combatant engagements are achieved by threats the defeated aircraft never saw. Identification may become a serious problem, especially after the first pass is completed and the aircraft groups become intermixed (or at least less formal in their structure). The actual air-to-air engagement will be described as a separate section.

Perhaps the most difficult task in this mission will be deciding what to do in the heavily jammed environment, which may severely degrade sensor performance. With target information limited to angle only at any instant, deciding which targets are most threatening to ownship and when to fire becomes a very complex task. When the number of participants is small, the system (including the pilot and his wingmates) may be able to handle the decisions fairly well. However, as the number of threats increases, the system may not be able to cope in real time.

B.3 GROUND-LAUNCHED CRUISE MISSILE (GLCM) DEFENSE

A major attack capability for both NATO and WPN forces in the 1995 time frame will be ground-launched cruise missiles. These are best used to attack fixed-location targets such as air bases, fuel dumps and communication centers. The GLCM is characterized by a very small radar cross section, terrain-following flight path, and subsonic flight. Several factors distinguish the GLCM attack (and subsequent interception) from the manned bomber attack of the Defensive Counter Air mission described earlier. First, the GLCM's are considerably smaller than the manned penetrators and do not attack in large groups. Second, they are unmanned and thus cannot be discouraged by the destruction of other members of the penetrating force, that is they are intent on attacking their designated target and will persist until they are shot down. Finally, the cruise missiles are unarmed and unescorted and thus do not offer any resistance or threat to the interceptor. The GLCM's will fly a preprogrammed flight path with built-in course changes to complicate any attempt at interception. They proceed to the target area at very low altitude (< 500 ft). Upon nearing the target area they execute a pop-up maneuver for target lock-on, followed by a steep dive towards the target. It is the job of the interceptors to destroy the GLCM's before their terminal maneuvers begin.

Early warning of the inbound GLCM's will be provided by ground radars. A degradation of detection range to 60% of the range for fighter-size targets can be expected, due to the small radar cross sections and low altitudes. The AWACS is of little value for this mission because it will not detect the inbound raid in sufficient time to scramble the interceptors and achieve interception. Upon detection, interceptors are scrambled from air bases approximately 320 Km behind the FEBA and fly out towards an intercept position at low altitude. The most critical step in the engagement process will be detection of the GLCM's by the interceptors. Like the ground radars, the interceptor

The next major phase is that of pre-launch. Here the fighters must meet in their predetermined groups and proceed towards the threat. The objective is clearly to attack and defeat the raiders before they split and head for their individual targets. Most scenarios examined have the raiding formation remaining intact until it penetrates the heavy defenses around the FEBA, counting on its large numbers to minimize attrition during the penetration. Vectoring towards the strike group is provided by NATO GCI. With this vectoring assistance, target detection (including group identification) should be limited only by sensor range. It should be noted that NATO sensor performance will probably be degraded by the jamming. This degradation could include complete denial of range information, with only strobe or sector information available. Detection may not occur until burn-through range in some cases. The defeat of the jamming to allow detection by the ownship sensors will be a critical factor in the mission's success.

After detection, the next step is raid assessment--separation of the fighters from the fighter escorts. In general, the escorts can be expected to be above the bombers, which should ease this critical but not overly difficult task. As the interceptors approach the threat group and are detected, a number of the strike escorts will break away from the formation and prepare to engage the incoming interceptor group. Each interceptor group will react to the escorts in a manner depending on the role of the individual interceptor (attack the bombers or engage the escorts). This reaction could be either predetermined or decided upon en route by the flight leader. The two sub-missions place different demands on the air combat system. If the interceptor has been tasked to attack the bombers, his first step must be to attempt to bypass the escorts. This is a critical step, as he cannot expend his limited ordnance against the escorts and still have enough to do sufficient damage to the bomber group. Planning a new route that evades the escorts is a time-critical task that comes at a very demanding time for the pilot. While he is replanning or executing a new route, he must be on constant watch for attacking escorts, while at the same time watching for changes in the bomber group heading that will adversely affect the ultimate attack geometry. Attacking escorts can appear at any time, both from those that broke off to engage the interceptors and from those that stayed behind to protect the bomber group.

Assuming the interceptor evades the escorts, his attack on the bombers will occur near maximum weapon range. The mission of the bomber group will in general keep it from making the kind of course changes that would affect weapon performance dramatically. Critical steps in the actual launch phase will be singling out specific targets from a closely grouped threat package, deciding on how many weapons to fire and when, kill assessment, and steering for another attack if possible. Many of these functions will be quite similar to those in the AWACS defense, except that the bombers are not a serious threat to the interceptor and the launch window is much larger because of a more favorable geometry. The goal is to achieve missile impact before the bombers can unload their ordnance. Depending on the number of NATO interceptors, the attack strategy may be to make only a single pass and then clear out to allow the trailing interceptors a "friendly-free" engagement.

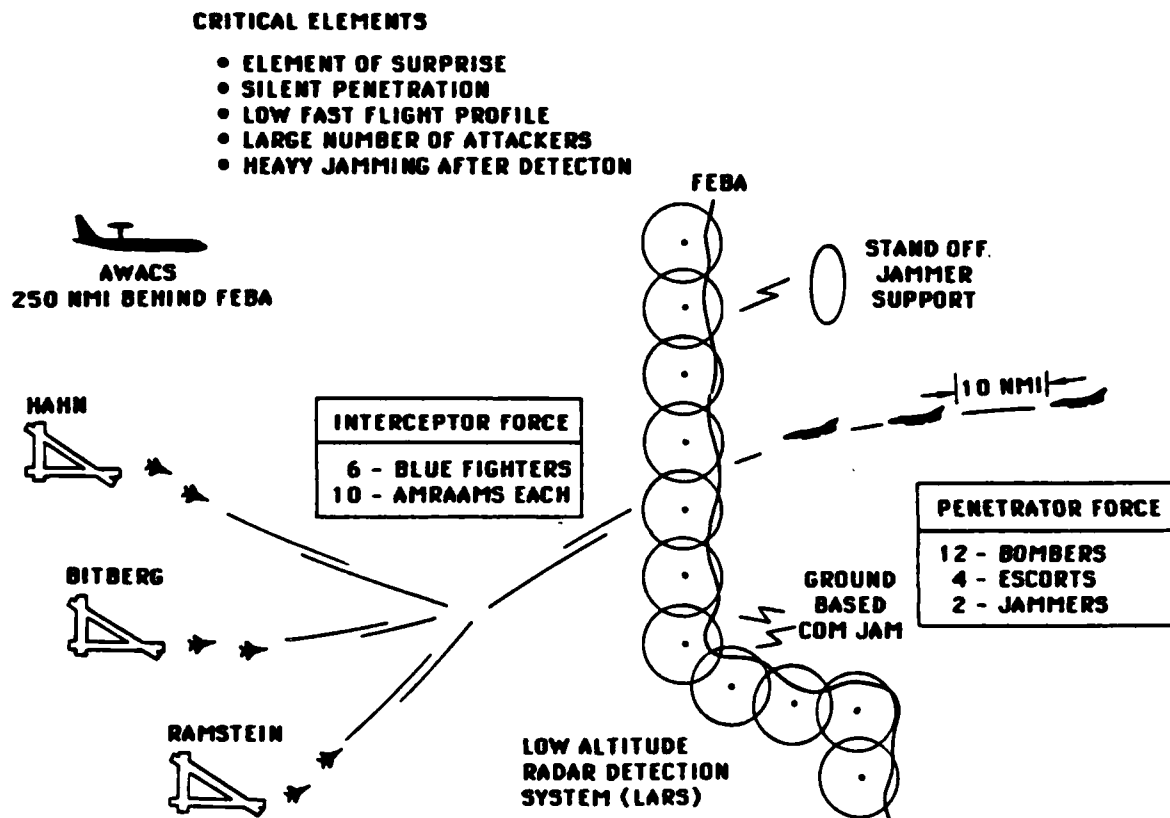


Figure B.2 Penetrator Defense Scenario (1995)

fighters acting in the roles of fighter sweep and escort. Initial penetration will be at low altitude, with complete suppression of radio and rf emission to hinder detection.

The essential features of this basic scenario are 1) the element of surprise on the part of the enemy, 2) the preplanned silent penetration, 3) the low and fast flight profile, 4) the large number of attacking aircraft, and 5) a heavily jammed environment once the attackers feel they have been detected.

Air defense forces from the bases under attack are committed to the destruction of the penetrating forces. Initial raid detection will be provided by NATO early warning radars deployed to provide coverage across the FEBA. They will in turn relay information to the appropriate command center, where the information will be processed, a reaction will be determined, and resource deployments made. NATO interceptors will be scrambled from a number of bases to intercept the penetrating raid. They will be under GCI control, with inter-ship secure communications also available. Additionally, it is likely that CAP stations will be set up and some interceptors will be sent from those stations within intercept range. Some groups of the NATO fighters will engage the escort fighters, while other NATO groups may try to avoid the escorts and engage the bomber force. Depending on the relative numbers of fighters in the opposing forces, all NATO fighters may have to engage the escorts before attacking the bomber force. Figure B.2 provides a pictorial representation of the basic mission scenario.

The DCA mission requires the interception of a very large number of attacking aircraft at low altitude. The target group will consist of three basic types of aircraft--fighters, bombers, and jammers. Several types of fighters will probably be encountered. The primary mission of the defense interceptors is to stop the bombers from reaching their assigned targets, i.e. the air bases or other high-value ground targets.

The strip launch interception appeared to be a more demanding task than the CAP station response for this mission, so it was chosen for study. There are a number of mission phases that can be identified--the scramble on the ground to launch the interceptors, rendezvous as necessary with other NATO fighters to coordinate the attack, planning of the attack, threat detection, raid assessment, establishment of the multiple target track file, and the actual attack run, including assessment of kills and the potential for re-attack.

In all likelihood, the interceptors will be on five minute alert on the ground. Prior to the actual scramble, the expected enemy formations, tactics, and anticipated engagement geometries will have been analyzed and discussed among the crew members. The scramble routine is well established and is practiced diligently. There is probably no significant role for AI in this phase. The importance of the phase is critical however. Every second wasted will decrease the available time for planning and conducting the actual interception and will ultimately erode the safety of the home base.

consequently they offer little support until the pre-engagement phase begins, at which point the CAP aircraft are vectored towards the attacking force.

The first function after the CAP aircraft are turned towards the attacking force is target detection. The AWACS will supply threat cueing to the CAP aircraft, which is critical given the large number of aircraft that could be within its search volume (quite likely 100 or more). Clearly the critical challenge to the air combat system during this phase will be the sensor management and target identification functions. The high closing rate associated with this mission compresses the time available for accomplishing this task, and sorting out the threats from the friendlies is obviously critical to the mission's success. Too long a delay and the enemy fighters may get within attack range of the AWACS before encountering the CAP aircraft--a mission failure. Premature targetting may lead to fratricide--an unacceptable occurrence and essentially a mission failure. The threat geometry (high and fast) should somewhat lessen the confusion with non-threatening aircraft, as there will be few if any friendlies operating with geometries similar to that of the threat. The other function associated with the target identification will be an assessment of the raid. The assessment requires a count of the raiders as well as sufficient target resolution to allow NATO weapons to select individual targets.

After the threats have been identified, some form of prioritization and battle planning must take place. Operations here include coordination with the wingman, launch ordering for those targets assigned to ownship, and maneuvering for tactical position as necessary. Again, it is important to note the extremely limited launch envelope against this target package. The small launch window emphasizes the need for the interceptor to arrive at the engagement area in a satisfactory fighting posture in both speed and altitude. This will require on-line adjustment of the flight parameters to reach an optimum firing condition at the required time.

The actual engagement will take place at well beyond visual range. Critical events in this phase are the decisions on when to fire and how long target illumination is required, assessment of the threat against ownship, kill assessment, and determination of when to break off the attack. The threat geometries and speeds are such that the entire phase of the first (and only) pass may last less than one minute (with an even shorter time for possible launches), and therefore quick reactions and decisions on the part of the air combat system are mandatory.

B.2 DEFENSIVE COUNTER AIR

This mission represents an air defense situation likely to occur in Central Europe. In the early hours of a conflict, WPN forces will attempt to destroy high-value NATO resources with waves of fighter and bomber aircraft and accompanying jammer aircraft. The objective of the raids will be air bases and supply bases located approximately 250-300 Km behind the FEBA. The raids will be channeled into several predetermined corridors, with multiple waves of bombers accompanied by

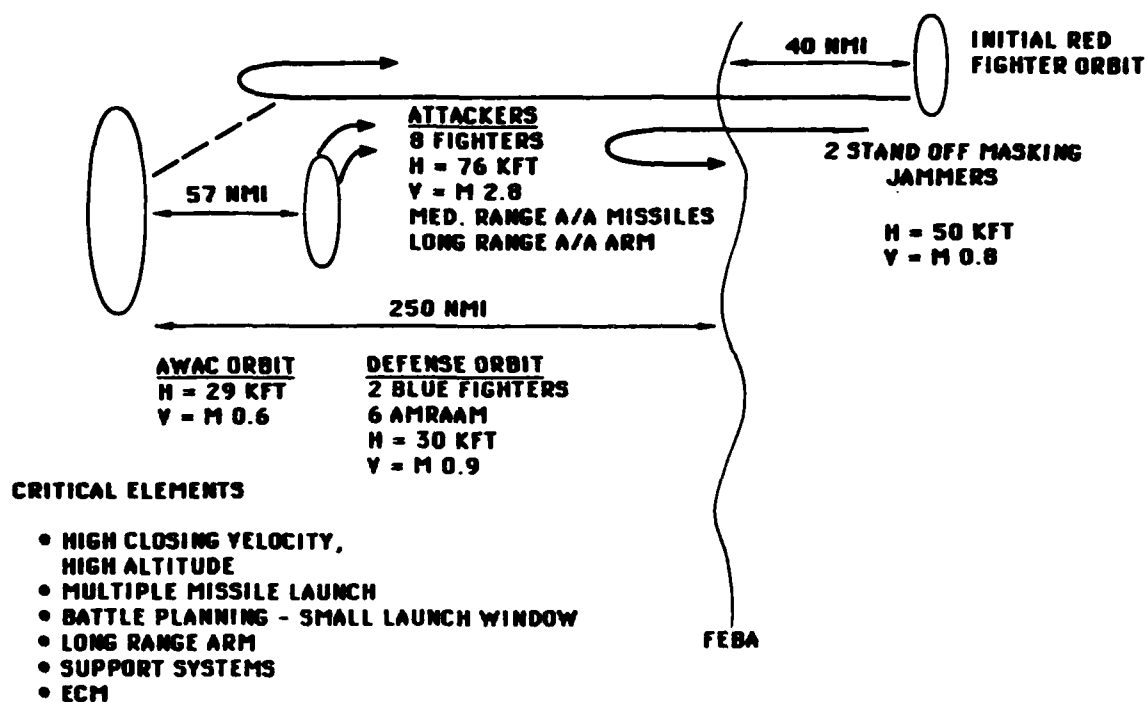


Figure B.1 AWACS Defense - 1995

The AWACS has a long-range detection capability against fighter and bomber targets. This permits detection of a threatening aircraft in ample time to plan its interception and deploy the necessary elements. Obviously, if its capability to direct interceptors to their target is destroyed, the AWACS' mission is largely negated.

A typical attack on an AWACS would be carried out by a flight of 8-12 enemy fighters. The attackers would emanate from an orbit approximately 80 Km behind the FEBA at a relatively high altitude. They would climb to very high altitude and accelerate to high speed before crossing the FEBA to attack the AWACS. Their penetration would be masked by two standoff jammers. Each enemy fighter is projected to have a long-range attack capability against radiating targets, using an air-to-air ARM missile.

The defense strategy for the AWACS is to orbit two CAP aircraft 15-35 Km in front of it at medium altitude and sub-sonic speed. Figure B.1 summarizes the AWACS defense mission and a rough scenario.

There are several key features in this mission. The available reaction time for the NATO aircraft is quite short due to the very high closing rates of the attackers. An added confusion factor will be the large number of friendly forces operating in the general area. This will include low-altitude aircraft such as helicopters and A-10's operating near the FEBA, as well as friendly fighter sweeps and/or strikes operating beyond it or on the friendly side of the FEBA as they return from missions. The combination of compressed timeliness and slower attack recognition due to crowded air space makes this a very demanding mission. Furthermore, weapons performance of the opposing forces may be roughly comparable, which compresses the timeline even further. Finally, the flight profile of the threats creates a very adverse launch environment for the CAP aircraft. The possible launch envelope against the high, fast target is extremely limited, both in duration and in acceptable approach angle.

Once the CAP station is reached, this mission has relatively few phases--a pre-engagement phase, a pre-launch phase, and the launch or engagement phase. The pre-engagement phase begins with the AWACS detecting the enemy fighters crossing the FEBA at high speed and high altitude. Prior to this the jamming has masked the enemy's grouping activities. The penetrators are under GCI control and are not radiating with their sensors. The standoff jamming has been defeated by the AWACS sensor suite by the time the fighters cross the FEBA.

Since the AWACS is a control center and has dedicated defenses (in the form of CAP), it has the capabilities required to commit the orbiting CAP aircraft to engage the enemy fighters. Because of the large number of aircraft under surveillance by the AWACS, there will be delay in recognizing the attack as being against the AWACS and in commanding the CAP aircraft to engage the attackers. It is at this point that the mission formally begins for the CAP aircraft. Prior to this, they have simply been orbiting and waiting for direction from the AWACS. Their sensor capabilities are inferior to those of the AWACS and

APPENDIX C

AIR-TO-SURFACE AND OTHER MISSIONS

C.1 AIR TO SURFACE MISSIONS

Air-to-ground missions place a different set of demands on the air combat system from those of air-to-air missions. They are classically more formally planned, both in terms of targets and tactics, than air-to-air missions. It may be possible to take advantage of this formalization to enhance mission effectiveness with AI technology.

Many air-to-ground missions involve fixed targets, such as air fields, factories, and dams, and the routes to reach the target areas are explicitly defined. This differs from air-to-air missions, where targets are highly mobile and there is little preplanned guidance to the targets because of their unpredictability. Ground targets differ in the level of their defense. Generally, important ground targets will be more heavily defended.

Air-to-ground missions are characterized by a greater variation in the number of friendly participants. Numbers of friendly aircraft can vary from one, in close air support, to literally hundreds in a deep strike mission. This will affect communication requirements placed on the air combat system as well as allowable tactics. Attack aircraft may also have a larger variety of weapons at their disposal, ranging from air-to-air weapons for self-defense to bombs, missiles, rockets, and guns for the actual ground attack. The wider choice of weapons provides more alternatives for attack, which may be either a positive or a negative factor. The different weapons provide flexibility in the attack, which may be useful in some circumstances. However, a choice of alternatives can be negative if time to make a decision becomes short and the number of alternatives to consider is large.

There are dozens of variants of air-to-ground missions. Nearly every pilot has his own list and definitions of missions. A cross section of opinions and mission definitions is reflected in references 11-19. Recent interviews with F-16 air-to-ground pilots were also helpful in the definition of missions (ref 20). This study contains a selection of the most meaningful missions and those that place the largest demands on the air combat system for further study. Army, Navy, and Air Force missions were considered, with much commonality found among missions for all three services. Targets and tactics differ somewhat but the basic demands placed on the system are quite similar, particularly with respect to which tasks are most difficult and critical. The six air-to-ground missions selected for study are: close air support, interdiction, deep strike, anti-shipping, armed reconnaissance, and vertical assault.

C.1.1 Close Air Support (CAS)

A likely objective of U.S. military action may be to provide crisis control or to prevent military collapse of a friendly nation. Thus, during Naval activities, air support of indigenous troops, Marine amphibious troops, and Rapid Deployment Forces, will be important. This close air support may well take place in nonpermissive situations in which enemy fighters from forward airfields, mobile anti-aircraft artillery, and SAM activity are encountered. Averting military disaster may well require around-the-clock amphibious and airborne operations. Until air superiority is established and the enemy fighter threat is significantly reduced, close air support may be difficult. Initial air operations in support of amphibious and land-maneuver elements must expect to encounter significant gun and missile opposition.

A similar mission exists for the Air Force and Army, that being support of front line troops near the FEBA. Other than the staging details, most of the mission description is identical, regardless of whether the focus is on the Army or Air Force mission.

The basic close air support mission calls for carrying a large expendable payload (that is, free-fall bombs, cluster weapons, guided weapons) to a radius of up to 200 nmi on internal fuel only. The use of guided weapons requires close coordination with the ground forces to meet safety requirements for friendly forces. (True for all weapon types but more strictly so for guided weapons). In most cases, weapons will probably be delivered at ranges short of the required 200 nmi. The targets of concern will be found close to friendly troops, at the FEBA, and the attack will require close coordination with the troops. Particular targets of interest may include any or all of the following:

- troops in various postures (dug in, in the open, etc.)
- tanks, individually or in columns
- small, lightly armored vehicles
- self-propelled guns and SAM's,
- mortar positions
- bunkers
- artillery gun placements
- small supply dumps or caches

The strike aircraft will usually receive target assignments from the forward air controller on the ground after having been directed to his vicinity by the Direct Air Support Center. Flights will originate in various ways depending on the phase of the conflict: from the carrier deck (or a rear air base), from airborne loiter, from captured airfields ashore, or in the case of VSTOL aircraft like the AV-8B, from landing ships, expeditionary short airfields, or pads immediately behind the FEBA. Assignments from a forward air controller (FAC) airborne could be made in a permissive environment; current Soviet Motorized Division air defense assets preclude airborne FAC. The attack will be controlled by the forward air controller, since the pilot must accurately know the FEBA and the bomb line (i.e. the no-fire line, beyond which the absence of friendly forces makes it safe to drop bombs at will). The weapons used against troops and small vehicles will normally include bombs, napalm, cluster weapons, rockets or guns. Weapons used for tanks and

other small, hard targets include bombs and missiles of the Walleye/Maverick type. Delivery methods will include level laydown from 30 to 600 Km, dive and glide angles from 10 to 60 degrees with release points ranging from 600 to 1500 Km, loft, toss and level bombing, with control exercised by the Forward Air Controller. For weapons requiring illumination, either the CAS aircraft or a ground source could illuminate the target.

Major issues of concern in this mission are close coordination with the ground forces, extension of attack capability into degraded weather while maintaining friendly force safety, increased weapon delivery accuracy, and increased survivability against point defenses. Coordination with FAC calls for FAC beacons, improved navigation vectors to FAC location and improved, secure, jam-proof voice communications between Direct Air Support Center, pilot and FAC. Improved weapon delivery accuracy can be achieved by FAC/laser target designation schemes and ground force commander's acceptance of these homing weapons (acceptance is related to own troop safety and confidence in accurate delivery); however, these deliveries, being laser dependent, do not extend into limited-weather definitions. Requirements for delivering weapons in poor weather in the close air support role are poorly defined and may well be untenable. Further, the use of lasers or other designation devices increases the exposure of whoever is doing the illuminating, as the radiation effectively acts as a beacon to the enemy, advertising the position of the illuminator. Communications equipment improvements and communications net provisions must address the problem of strike control and coordination. This becomes particularly evident when the proximity of friendly troops and the attendant need for cautious weapon delivery are recognized.

The two key functional issues that will largely determine mission success are:

- * Target Detection - With good communications, the FAC supplies cues and directions for CAS targeting. Factors which can complicate targeting (particularly for one-man crews) are weather states, the target background and surroundings, the target signature and communication jamming.
- * Survivability - Since very little overflight of hostile enemy territory is involved in the CAS mission, the emphasis on survivability is in the target area. Heavy opposition is expected during target acquisition, weapon delivery and escape maneuver from point defense weapons ranging from small arms, heavy machine guns and light AAA to hand-held IR seeking missiles. In addition, SAM systems located in depth behind the FEBA can place a CAS mission under fire from considerable distances. During this period, the aircraft may have very different and conflicting requirements for maneuvering--one for offensive positioning for weapon delivery and one for defensive maneuvers against threats. Tactics and flight control

selection will be a critical task for the air combat system. As in all missions, survival is of the utmost importance but the mission must be completed whenever feasible. These two statements will often result in dramatically different optimum tactics, which somehow must be combined to determine the overall best approach.

Clearly, to achieve CAS mission effectiveness, survivability can be enhanced by using Electronic Warfare techniques to include self-protection jamming and deception, stand-off jamming, and SAM suppression with anti-radiation missiles from supporting aircraft. But effective use of these measures can be inhibited if the pilot is overloaded or uncertain about the proper set to use against the threats. This uncertainty can be caused by a number of factors, including a lack of awareness about all potential threats, inability to identify a threat, focusing on other tasks such as weapon delivery, or many others.

Task loading for crews during target acquisition and weapon delivery will be heavy, with the requirements for target detection, communications with FAC, accurate weapon delivery relative to own forces, radar warnings, selection of countermeasures and tactics all having to be met nearly simultaneously. Depending on the situation, performance of any or all of the above tasks could deteriorate as the situation becomes more stressing, the level of threat intensifies, and the pilot becomes more preoccupied with particular tasks.

C.1.2 Interdiction

Interdiction to delay and/or disrupt enemy reinforcements or support elements is a major mission for airborne support of a ground conflict. In connection with amphibious, airborne or ground-based counterattacks, interdiction to isolate the battlefield will be required. Defenses will tend to be heavy, including both gun and SAM systems (many mobile) in area locations and in point defenses. In many cases initial targets will be "hard". As they are attacked, repairs will produce "softer" targets. The enemy electronic environment will be sophisticated and difficult to counter.

The interdiction mission calls for carrying a heavy payload to a moderate radius with external fuel. The objective of this mission is the interception and destruction of troops and supplies moving to the front lines, or the destruction of their lines of transportation. Targets may be either pre-briefed or targets of opportunity, and may include any or all of the following:

- bridges
- roads
- railroads
- tunnels
- communications facilities
- vehicles
- troops.

Weapon types are of the same variety as those used in the CAS mission, except that wider use can be made of unguided/guided missiles, since the requirement for close coordination with friendly forces does not exist. In addition to these weapons, the Anti-Radiation Missile (ARM) family, AGM-78 (STANDARD ARM) and AGM-88 (HARM), can be used to suppress/destroy radar sites providing anti-air coverage along supply routes. Delivery methods include low-altitude laydown, dive, glide, loft and toss. Approach altitudes, dive angles and release altitudes will be dictated by survivability, target acquisition and target kill considerations, with no initial boundary limits as in CAS, where target acquisition and weapon delivery relative to friendly forces is of utmost importance and can shape the delivery conditions.

Since for concealment purposes the moving targets concerned (troops and vehicles) would often be moved at night or in foul weather, the ability to navigate and to acquire and attack targets under limited visibility becomes quite important. The interdiction mission may also require several hundred kilometers of flight over enemy-held territory. Hence, to avoid detection, these missions require a lengthy period of terrain following; this requirement places a greater emphasis on accurate navigation and the use of sophisticated radar and/or electro-optical sensors. Radar homing and warning systems and defensive electronic countermeasures (DECM) are essential.

Major issues of concern in this mission, for any advanced attack system definition, are navigation; terrain following for some portion of the flight; target acquisition, across a weather spectrum ranging from clear day to adverse weather, to allow accurate weapon delivery on the first pass; avoidance of airborne and surface threats; and the ability to effectively utilize defensive electronic countermeasures.

Navigation requirements are dictated by lengthy low-altitude flights over enemy-held territory in poor weather (assuming a worst case). Targets which are pre-briefed in detail (bridges, rail centers), both with respect to geographical coordinates and position relative to prominent landmarks, will possibly be easier to acquire and identify. However, they will tend to be very heavily defended, making the element of surprise and first-pass kill effectiveness mandatory. Precise navigation will be required to allow entry into the target area at offsets from the target that allow first-pass target acquisition, weapon delivery and kill.

Terrain following, even though of greater importance in the deep strike mission, can also be of importance in pre-briefed interdiction missions. Accurate minimum-altitude navigation becomes difficult in poor weather conditions, even with an automatic flight control tie-in, because the pilot's attention must be concentrated most of the time on monitoring the system operation. The ability to maintain correct position and track information and proper heading towards the destination becomes a function that the aircraft and system must be capable of performing with little or no aid from the pilot, as situation awareness is critical to survival.

Target acquisition in the interdiction mission, unlike target acquisition in the CAS mission, must be accomplished without the aid of vectors from forward air control and in potentially poorer weather. Radar, possibly high-resolution, must be used in many instances to cue electro-optical sensors for final location and identification for attack purposes. The acquisition of targets of opportunity from low-altitude flight profiles under conditions of low visibility requires that most of the pilot's attention be devoted to that function alone, and that control and navigation of the aircraft be accomplished primarily by the avionics system. Again, this tunnel vision on target acquisition can have a deadly effect as other tasks get bypassed or ignored.

The threat warning and DECM requirements are strongly dependent on threat densities. A primary consideration for all electronic warfare (EW) equipment is that it should be fully automated to free the pilot/crew during critical situations. For example, one requirement is the use of automatic switching among various jamming techniques while maneuvering. Full coordination between EW control and other functions may offer large payoffs. As with many other missions, selection of a defense against threats, whether soft weapons such as chaff/flares, jamming, evasion, or engaging, will be critical in determining mission success.

C.1.3 Deep Strike

Destruction of enemy targets (military installations, dams, power plants, factories, etc.) at long distances from base will be required in most engagement theaters. Counter-air aspects of the deep strike mission requirements are addressed by strikes on enemy airfields. Extensive hardening of main airfields will resist destruction of parked aircraft on a large scale and will require attacks on runways, buried petroleum oil lubricants (POL) and similar facilities. Improvised and dispersed airfields may be encountered in number and, although not hardened, will be well camouflaged.

The deep strike mission calls for carrying a payload of 2000 lb to a radius of 800 nmi with external fuel. In limited warfare, the tactical targets will be located far from the front lines and may require attack with high-yield conventional weapons. These weapons will be either laser-guided modular glide type, of the MK-83 LGB variety, or standoff guided missiles and all weather variants thereof, plus an entirely new family of standoff guided missiles capable of maneuvering off the line of aircraft heading so that they can be command guided to targets acquired by side-looking synthetic aperture, high-resolution radars. Alternatively, unguided "dumb" bombs may be used, as they require no emission on the part of the strike aircraft. A non-emitting profile may offer survival advantages that outweigh the accuracy advantages of guided weapons that require illumination.

As with the interdiction mission, threats could appear at essentially any time, both from the ground (SAMs and AAA en route and at target) and from airborne fighters. Early detection of threats will greatly enhance the survivability of the strike aircraft. Of particular interest will be passive detection capability, as emitting sensors are a beacon signal to the enemy. Once engaged, reaction to the SAM or AAA is

obviously critical to survival. As in the airborne missions, there is a large choice of defense reactions, ranging from kinematic maneuvers (early, to outrun the weapon, or end-game to cause a miss) to flares and/or chaff to jamming. Timely choice of the correct action and proper execution is an extremely difficult task that may require assistance. The task is only made more difficult when the threats encountered are located near the ultimate target, where the strike aircraft is engaged in weapon delivery.

The deep strike mission places the most stringent demands on terrain-following/low-altitude navigation capability. The use of electronic warfare for defensive purposes and as a penetration aid also becomes more important. Additionally, an automatic flight control system coupled to the terrain-following radar would improve the safety and fatigue factors normally associated with long periods of flight at minimum altitude.

Major issues of concern in this mission, for any advanced attack system definition, are similar to those of the pre-briefed interdiction mission discussed earlier. This is particularly true for navigation, target acquisition, weapon delivery, and DECM requirements. The major difference will be that low-altitude penetration portions of the flight will be longer than those for interdiction and although targets will be larger and more readily acquired, they will be even more heavily defended than interdiction targets. The emphasis on precise navigation, terrain following, first-pass acquisition and conversion, with complementary EW capabilities, complicates the interdiction requirements and adds another level of accuracy and autonomy requirements.

An additional issue raised by deep strike mission requirements is the use of standoff missiles. These are more likely to be used against deep strike targets, because these targets are invariably of high value and their numbers are more commensurate with the use of more expensive weaponry. Moreover, they are heavily defended, and if effective attacks must be made against them, the only cost-effective manner may be with standoff missiles. The use of advanced guided missiles would impact directly on avionics definition, particularly radar requirements and weapons management.

C.1.4 Anti-Shipping Mission

Warships (and submarines) armed with surface-to-surface missiles, both on the high seas and in coastal waters, may be prime targets for carrier-based aircraft. Submarine support facilities, ranging from underground pens to tenders at remote anchorages, will exist in most conflict areas. Ship defenses are formidable with various SAM systems, all with electro-optical track back-up capability, deployed by all major combatants. Naval gun AAA capability will be encountered, particularly new rapid-fire, multi-barrel, point defense systems.

The anti-shipping or surface attack mission requirements are similar to those of the interdiction mission, except that many targets would be encountered on the high seas instead of on land. A requirement for the mission would be to carry fairly large payloads to long ranges, carrying external fuel. The objective of the mission is to

neutralize/destroy naval combatants armed with surface-to-surface missiles, disrupt sea lines of communication of the enemy, and attack harbor and submarine port facilities. Targets will vary and cannot be covered in a single list with generalized requirements pertaining to the mission. Possibilities include:

- * Major combatants such as cruisers and destroyers (heavily armed)
- * Lightly self-armed aircraft carriers such as the Soviet Kiev class (Note: Fighters may be scrambled to intercept the strikes)
- * Lightly armed transport or UNREP ships
- * Unarmed transports

If the rules of engagement are to find the enemy and destroy him, in other words, if a general war-at-sea exists, major surface combatants equipped with surface-to-surface missiles can become targets of opportunity along with the forces they support. In this case, the critical elements of the mission resemble those of the interdiction mission. The added difficulty of having to fly over large ocean areas with no prominent identification points (IPs) or fix points imposes the requirement for precise onboard navigation, with updates preferably from navigation satellites. However, the absence of a FEBA and its attendant defenses makes the target ingress simpler and less demanding.

If general war-at-sea open engagement rules do not apply, that is, if the friendly attack system must wait until a positive indication is made by the enemy combatant that a surface-to-surface missile is about to be or has just been fired against friendly resources, then the critical mission element is prompt reaction. This can only be achieved by "shadowing" the enemy, remaining in airborne attack stations in close proximity and using standoff weapons against the combatant, and/or air-to-air weapons against the cruise missile if it is launched.

The destruction of missile platforms requires penetration of heavy ship defenses, whether by aircraft system in concert with its weapons, or by launched weapons alone. In both cases, heavy reliance must be placed on a combination of Electronic Warfare techniques involving onboard DECM, expendable jammers, stand-off jamming, anti-radiation missiles, and decoys.

As with all missions discussed here, survival is of the utmost importance and may lay intense demands on the air combat system at times. Threats will consist of the self-defense weapons of the ships being attacked (and their escort ships) and of aircraft launched from nearby ships. The strike aircraft will normally have escorts to engage the interceptors, but the threat of attack by the interceptors on the strike ownship is still a very real concern. Defense options are quite similar to the deep strike mission except that there is no terrain to mask with.

C.1.5 Armed Reconnaissance

An armed reconnaissance mission is designed to destroy targets of opportunity, with a secondary mission of attacking specified fixed targets if no target of opportunity presents itself. The objective is the same as that of the interdiction mission, as are the targets. Armed reconnaissance, however, is generally planned for a specified route or area, and weapon payloads may be tailored to attack moving or movable targets.

C.1.6 Vertical Assault

All of the missions described so far are for fixed wing aircraft. There is a whole class of missions involving helicopters in which the Pilot's Associate could play a meaningful role. One of these missions is Vertical Assault. The objective of the Vertical Assault mission is the destruction of enemy defenses, seizure of landing beaches, and securing the beaches to prevent reinforcement by enemy forces so that a successful landing by the main amphibious force, using ships and landing craft, can be achieved (reference 11). For the 1995 time frame, the mission requirement imposed by the Marines is for the helicopter (such as JVX) to be capable of landing the assault elements of a Marine Amphibious Force (MAF) ashore in not more than two waves within a time span of no more than 90 minutes, without refueling.

Vertical assault missions are generally flown in flights of two aircraft, with multiple flights operating in coordinated groups as a function of the size of the assault team. Some scenarios include escorts flying with the assault helicopters. The site of a particular scenario could be any hot war situation involving MAF operations. Particular theaters include the Jutland Peninsula in northwest Europe, somewhere in the Sinai (Eastern Mediterranean), and a Pacific checkpoint such as Sundra Strait. The specific theater is important only in recognizing the relative seclusion from nearby friendly land forces associated with this mission.

The low-altitude flight profile of the Vertical Assault mission (as well as its very nature) exposes the helicopter to a wide variety of threats, including small arms fire, machine guns, anti-aircraft artillery (AAA), SAMs, and air-to-air missiles from fighters. Each of these can pose a significant threat requiring potentially different reactions on the part of the helicopter.

Helicopters used (or projected to be used) in the Vertical Assault mission are generally lightly armed. Armament might include air-to-air and air-to-ground guns, rockets, or air-to-air and air-to-ground missiles in small numbers. Since their primary mission is the landing of the assault team, they will try to avoid engagements with enemy forces when possible within the context of their mission. However, when forced, they could attack other helicopters, ground personnel forces, and ground weapon sites (AAA and SAM).

Pre-launch briefing and intelligence reports play a large role in this mission. Route planning is carefully coordinated to avoid known enemy strongpoints or positions and to reach certain points at the

desired time. Mission timing can be critical when other air support is used to soften the landing area. After the pre-launch brief, the helicopters and escorts making up the vertical assault team take off from their host ships with the troops and supplies and proceed to the rendezvous point. When all the team is at the rendezvous point and ready, the formation departs for the first waypoint. The flight transits at 1100 meter altitude when over water, while the overland portion of the assault is flown at lower level, with the final penetration near the landing zone flown in TF/TA mode. The route is characterized by heading changes in excess of 90 degrees, with basic transit speed at maximum cruising power.

As the landing zone is neared, the flight leader sends escorts into the landing zone area to scout for conditions and enemy activity. The remainder of the flight holds in this position until the scouts return and report. Assuming all is well, the flight moves towards the landing zone, which has been marked by colored smoke. The helicopter then hovers over the landing area while the troops and supplies are discharged. This will take 120-150 seconds, during which the helicopter is quite vulnerable to enemy attack. After the troop drop, the helicopters rejoin in formation for the transit back to the mother ship to pick up the second wave. The transit route during the second wave may differ from that of the first wave, but the mission description is largely the same.

Threats can appear at virtually all points during the mission - from SAM's on board naval ships to small arms fire in the landing area. In general, the helicopter would rather avoid engagements and proceed with the primary mission so defensive measures are usually preferred over offensive. Recognizing that a threat exists obviously precedes choosing a course of action to defend against the threat. The wide variety of threats and an inability to detect some of them with sensors inhibits the recognition of a threatening enemy and may limit the alternatives available for defense. Therefore, situation awareness will be a critical requirement. Once a threat is detected, choosing the correct course of action in a timely manner and then executing the action is a demanding task. Depending on the threat, the menu of possible actions will include engaging with the helicopter's own weapons, calling for support from escorts, using chaff or flares, jamming, and kinematic maneuvering to evade/avoid the threat. Timing of many of these actions is critical in determining the level of success of the action, and often execution must be closely coordinated with sensor information. When fractions of seconds are critical, humans begin to lose their effectiveness, particularly with the high closing rates associated with many threats. The area of defense selection is one where the PA may be able to make a contribution.

Finally, any terrain following/terrain avoidance mission is demanding on the flight control system, as the margin for error is rather small. Fly too low and the consequences are quite obvious; fly too high and the aircraft loses its masking and raises its exposure. Tests have shown that TF/TA flying demands all the concentration of the pilot, leaving him incapable of taking on many other tasks. Clearly, if some of the burden of flying could be lessened he could contribute in other areas to a greater extent.

C.1.7 One-Man Light Attack Helicopter Mission

The complete mission description of the light attack helicopter (LHX) is not available at this time. However, one mission, Scout Attack (SCAT) seems certain to be utilized (reference 19). The primary emphasis of the SCAT helicopter mission is Close Air Support. While the mission is similar in its basic characteristics to fixed-wing Close Air Support, the tactics and requirements on the air combat system differ dramatically. The SCAT mission includes enemy SAM attack, deep strike attack, air defense against attacking fighters and helicopters, and anti-armor missions. Up to ten helicopters will form scout and attack teams, which will operate at or in front of the FEBA. They will operate with and without fire support by artillery and strike aircraft, by day or night, and often under adverse weather conditions. This type of operation requires one-on-one threat engagement capability and intra-team communications for the purpose of coordination of effort and reporting engagement status.

Typically, a SCAT mission begins at the Assembly Area, located safely away from the active battle area. This is the point where preflight briefings take place. The helicopter then proceeds at low level to its first assigned holding area (HA). It drops to contour or nap-of-the-earth (NOE) flight on its approach to the HA to avoid revealing the HA position. The pilot lands at the HA and is briefed about the specific mission to be flown. The briefing includes information about ground forces movements and maneuvers, fire support, and the objective of the operation. The helicopter again takes off and proceeds at NOE to its battle position, where the enemy is to be engaged. After the engagement is completed, it may return to the HA for reassignment or to the Forward Arming and Refueling Position (FARP) for supplies. At the close of its assigned activities, it returns to the assembly area. Figure C.1 is a flow chart representation of these activities.

The critical portion of the mission lasts from the time the helicopter leaves the holding area until its return to the assembly area at the termination of the mission. Flying NOE is extremely demanding of the pilot, who must for example be aware of the current threat situation, as reported by on-board electromagnetic/optical sensors and as directly observed, while maneuvering his vehicle so as to avoid low-altitude obstacles. Unanticipated threat actions can greatly increase the pilot's workload during this difficult phase. A mistake in judgement or a moment's distraction from the task of flying the helicopter during this flight phase is more likely to cause a catastrophic mission failure than is enemy action.

Upon arrival at the battle station, the helicopter will gain sufficient altitude to insure line-of-sight contact with the target, thus permitting the air combat system to perform the attack mission. During the time the helicopter is in this position it can be seen/sensed by the enemy (i.e. unmasked) and attacked. For this reason the pilot will try to limit his exposure to just less than the threat reaction time. At the end of the maximum exposure time, the pilot will descend to a very low altitude, below the line-of-sight to the threat (re-masking), and proceed NOE to a new location. This procedure will be

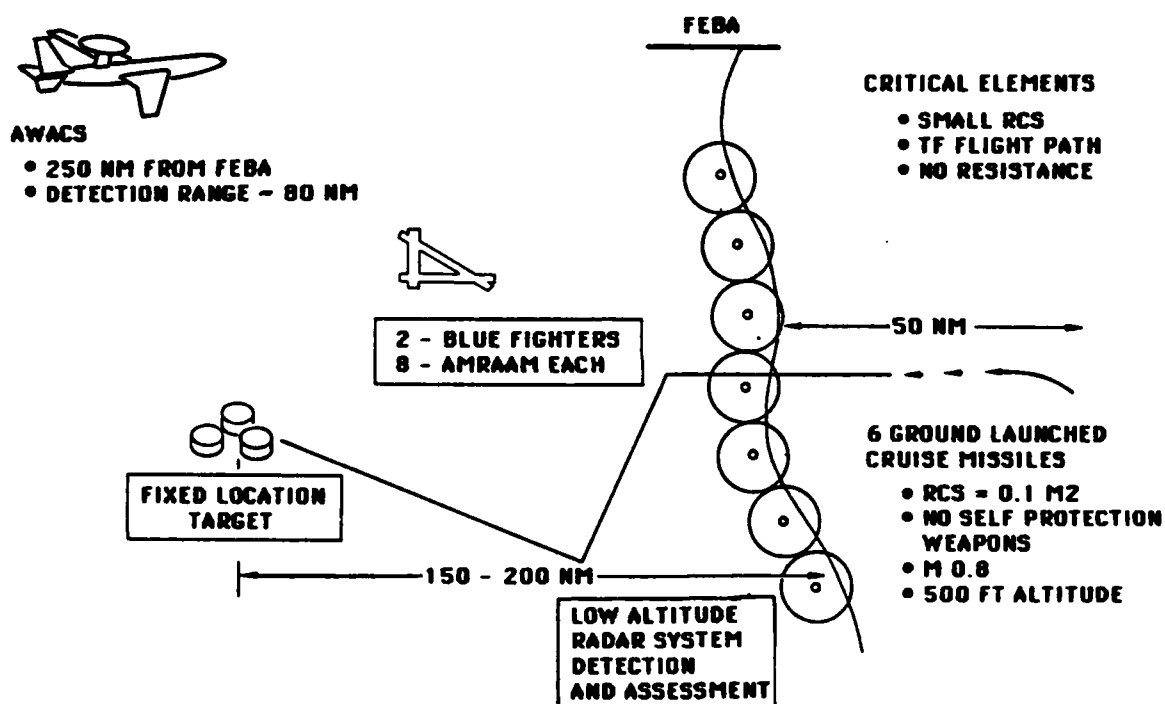


Figure C.1 SCAT Mission Functional Flow

repeated until the mission is either completed or aborted. During the time the helicopter is unmasked, the system must detect and locate the mission objective, identify it, and take the offensive action. Finally, by observation, the pilot must determine the result of his action. If the mission has been completed he may attack a new threat or target or he may return to the HA for reassignment. In practice, it may be necessary to proceed through several unmask-remask-move cycles while locating, identifying, and engaging the threat. Heavy use of countermeasures, particularly jamming, will make communications uncertain and the on-board sensor performance will be degraded. This will significantly increase the system workload during the most critical phase of the SCAT mission.

Depending on the particular scenario, there may be ground support available for target designation and weapon illumination. In this case, masked weapon delivery may be possible with weapons such as Hellfire. However, the helicopter will still have to expose itself for general region surveillance and to locate the target in general terms at least.

The most critical tasks here will be in the battle plan, i.e., choosing when and where to unmask and for how long to expose the vehicle. Within that short time frame, information concerning the target must be gained and either digested on the spot or stored for later assessment. The demands on the system during these bursts of activity will be manifold, including vehicle control, sensor management, visual surveillance, weapon control, and kill assessment.

C.2 OTHER MISSIONS

The missions described to date involve the ultimate delivery of ordnance at some stage during the mission. There are a number of air combat related missions that do not involve weapon delivery and that may be able to gain from technology associated with the PA program. None of these missions is perceived to be as stressing or demanding as the previous missions discussed but they have been included for completeness.

C.2.1 Cargo or Transport

Supply drops and resupply are necessary in any battle arena. The transport of supplies may occur over friendly or hostile territory and may or may not meet resistance from ground or airborne threats.

The sub-mission selected for review is a supply drop (or troop parachute drop) near or behind the FEBA. Depending on the flight profile, resistance could come from either ground threats (SAMs, AAA. or small arms fire) or from enemy fighters. The goal of the mission will be to reach the designated drop area (possibly at a designated time), drop the supplies or troops, and return to the base.

The key element here will be flight path determination to reach the drop area successfully. Pre-mission briefing will choose a transit path and designate the target or drop area. The task for the transport aircraft will be to follow the assigned path. However, there is always a strong chance the path will have to be altered because of enemy defenses, weather, or other factors. If this is the case, a replanning of the flight path that still allows reaching the drop area must be done in a short time frame. Considerations will include any rendezvous times at the drop area, fuel constraints, location of known enemy defenses, and weather. In certain flight profiles, the desire for low-altitude penetration may require terrain-following/terrain-avoidance as part of the flight profile.

The mission culminates when the drop area is reached and the supplies or troops are released. Considerations during the actual drop are monitoring flight conditions (speed and altitude), weather (particularly wind) and the drop site itself (is it as expected in terms of defenses, terrain, visibility, etc?). Contact will be kept with the drop leader to make a final determination on whether to actually make the drop.

After the drop is completed (or aborted), the final step is to return to the home base, again on some preplanned flight profile that may need adjustment along the way as a function of fuel, defenses, weather, and other factors.

Besides simpler and less time-constrained tasks, another major difference between this mission and weapon delivery missions is in the size of the air crew. Many transports have at least two crew members in the cockpit, with others aft in the aircraft. This spreads out the required tasks and provides some redundancy in capability.

C.2.2 Reconnaissance

Reconnaissance flights are used to gather information about particular enemy sites or regions. Specific targets for recon missions might include troop movements, fixed sites such as fuel dumps or factories, SAM sites, and air fields. The recon mission discussed here is a passive one - that is it is unarmed and flown to try to avoid detection and engagements.

The potential threats for this mission are the same as for the transport mission - SAMs and fighters. The reconnaissance flight profile is one of high altitude, so many of the SAMs will not be a threat, as well as some of the fighters. The primary element of this mission is one of proper navigation. One key to the entire mission is to get the photographs of the desired areas, which may require rather precise navigation. Another key element is survival, with the main threat coming from SAMs. The first step is to recognize that the recon aircraft is under attack, which will depend largely on the ship's sensors. Air crew workload should not be a major problem in this mission, as the recon portion of the mission is rather slow moving by comparison with other missions. If a launch is detected, the likely maneuver will be to increase altitude to try to outrun the weapon. Whatever the response, it must be decided upon relatively quickly to

make it effective. In general, recon aircraft may not have the aerodynamic capability to make a miss-inducing end-game maneuver, although that may always be a final resort if other responses have not been effective. Another possible response may be EW of some form-- flares, chaff, etc.

In summary, the key tasks in the recon mission are reaching the desired area for photography and, as required, response to weapon launches. These tasks are quite similar to some of those required in other missions such as deep interdiction.

C.2.3 Tanker

In the combat arena, refueling may be required on longer strike missions or possibly during CAP operations when fighter assets get thin. The purpose of refueling is essentially to lengthen the "legs" of other missions by allowing longer flight times.

Refueling is generally done in a non-hostile environment, so there are minimum threats to the tanker itself. It is possible that it could be jumped by fighters, in which case it would depend on the aircraft it is tanking or meeting with for protection. Alternatively, it has the same basic response capability as the recon aircraft.

The first task in the tanker mission is the rendezvous with the aircraft to be refueled. In some variations the tanker may fly with the aircraft it is to tank, but the more demanding mission involves a rendezvous. Key elements include flight profile and path planning to reach the rendezvous point at the designated time, sensor management to locate the aircraft to be fueled, the refueling operation itself, and the transit home. With the exception of the refueling operation, all the other key elements are very similar to those required for other missions and in general occur in a much less demanding time environment.

C.2.4 Combat Search and Rescue (CSAR)

The objective of the CSAR mission is to recover critical manpower in order to deny the enemy potential sources of intelligence information and to contribute to the morale and motivation of the combat forces (references 11 and 17). There are no "standard" CSAR missions - each mission is a unique situation requiring on-the-spot decisions. Whenever combat operations are anticipated over hostile territory, designated CSAR helicopter units are generally employed. The CSAR mission can be divided into four phases

- 1) Identification phase - A SAR situation is declared, the survivors are identified, and the SAR participants are organized.
- 2) Location phase - The precise location of the survivors is determined, as well as those of any hostile forces that might interfere with the rescue attempt.

- 3) Sanitation phase - Hostile forces in the SAR objective area are neutralized in order to effect rescue.
- 4) Recovery phase - This phase includes ingress, pickup, and egress by the recovery vehicle.

Only the last phase will be describe here in detail, as the other phases do not directly involve the SAR vehicle.

During the prosecution of the SAR mission, the aircraft may be subject to attack by a variety of enemy weapon systems. These include hand-held small arms, machine guns, anti-aircraft guns, SAMs, and fighters using guns and/or air-to-air missiles. The SAR vehicle is generally armed with guns, with its primary defense measures being evasion/avoidance and countermeasures such as jamming, chaff, and flares.

SAR-type helicopters are normally manned by four to five crew members: a pilot, co-pilot, one or two gunners, and a hoist operator. Each crew member has well defined tasks to perform during various phases of the mission. The discussion herein will focus on the duties of the pilot.

The mission formally begins with takeoff of the helicopter. Prior to this, a strike force participant has been shot down, with survivors positively identified. This information has been relayed by other strike force members via JTIDS. Within minutes, the SAR team has been assigned to attempt a rescue. The SAR vehicle could be located 160-320 Km behind the FEBA or on a ship the same distance from shore. The SAR team would have been involved in the strike mission briefing, so basic knowledge exists on force composition, communication channels, distress response coding, ingress/egress routing, potential threat sites, weather, and terrain conditions in the region of the strike route.

After takeoff, the helicopter will proceed towards the FEBA at 160-meter altitude at the speed for maximum range. Generally, the helicopter will follow the same route as that used by the strike group. As the FEBA is approached, the SAR helicopter will drop to an altitude of 30-60 Km or TF/TA, depending on the defenses around the FEBA. This profile will be roughly held until the survivor area is approached. Approximately 80 Km from the reported position, the SAR helicopter will perform an altitude pop-up to obtain range and bearing to the distress signal. Range and bearing will be found to around 1.6 Km accuracy at this range. Heading changes will be made as required. Transit will continue in TF/TA mode. At approximately 30 Km, another pop-up will be executed, which will refine range and bearing to around 7 meters. When the survivor position is within 800 Km, voice communication with the survivor will be attempted and identification codes exchanged. Upon visual sighting, the helicopter will hover over

the recovery area and use the hoist to bring the downed crew members on board. The helicopter then proceeds back to the staging site, normally along the same path as ingress.

Threats could appear at any time during the mission. The highest threat periods are during the penetration of the FEBA and during the actual recovery, when the helicopter is stationary. As the helicopter is lightly armed, it will avoid engagements and minimize exposure at nearly all costs. Threat defense will be the toughest part of the mission--deciding what action to take against the various threats and then taking the action. Important here will be the identification of the potential threat, as not all defense techniques work equally well against all threats. As noted in other missions, timing of the threat reaction is critical in determining the success of the action. Mistiming can be as disastrous as choosing an inappropriate action.

The other difficult portion of the mission is the terrain-following/terrain-avoidance flight profile. This is a physically and mentally demanding task that is critical to surviving. As threats are detected, TF/TA becomes increasingly difficult, since the normal response against particular threats may be to speed up, compressing the time for making decisions and maneuvering the helicopter.