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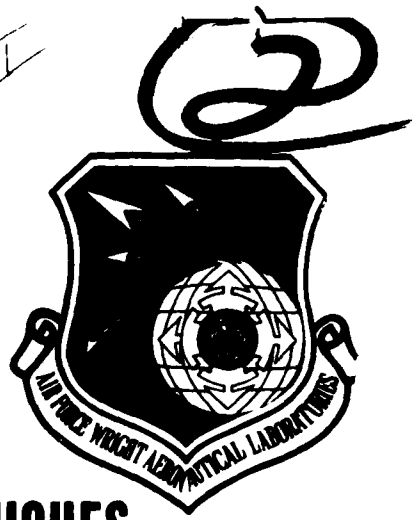

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INTEGRATED CONTROL DESIGN TECHNIQUES

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August 1981

FINAL REPORT for Period 4 June 1979-15 November 1980

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This technical report has been reviewed and is approved for publication.

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20. ABSTRACT (CONTINUE ON REVERSE SIDE IF NECESSARY AND IDENTIFY BY BLOCK NUMBER)

A total systems approach methodology and computer-aided design tool for integrated flight control design and evaluation has been formulated. This methodology is a composition of classical system design steps and system performance, reliability/survivability, packaging, and cost evaluation techniques assembled for interactive computer-based execution. The interactive sensor integration program developed under this methodology addresses the sensor requirements of the flight control, guidance and navigation, and weapon delivery functions as directed interactively by

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the designer and the mission, the system configuration, cost, power, weight, volume constraints, and total system performance. The demonstration program contains performance reliability, size, power, weight, cost data for gyros, accelerometers, radars, seekers, and air data systems in addition to analysis tools for evaluating navigation system accuracy, probability of target acquisition, and probability of kill for selected targets and weapons.

SUMMARY

Modern day avionics systems are becoming increasingly complex as the demand for better performance and higher reliability/survivability continue to escalate. These demands, however, are being pressed in an extremely cost-conscious environment. The Air Force Flight Dynamics Laboratory has spearheaded the development of flight control concepts which would integrate avionics subsystems both functionally and operationally in order to cost-effectively satisfy the demanding performance and reliability/survivability objectives. While achieving measurable success, these efforts concerning development of concepts have also uncovered a fundamental problem: there are no systematic design and evaluation techniques that directly address an integrated control system formulation. The integrated control design techniques and design examples described in this report are the first step in the solution of this fundamental problem.

These techniques and approaches were the product of a simultaneous top-down investigation of the total integrated control system design requirements and a bottom-up exercise of specific techniques on tractable subsets of integrated control system configurations. In summary, we believe the following accomplishments of this investigation are significant for ultimately realizing the fruits of integration:

- A total systems approach methodology and computer-aided design tool for integrated flight control design and evaluation has been formulated. This methodology is a composition of classical system design steps and system performance,

reliability/survivability, packaging, and cost evaluation techniques assembled for interactive computer-based execution. These techniques not only aid in integrated flight control system design but also provide, as outputs, system evaluation measures for demonstrating the value of integrated control. In addition, this formulation could be used as the foundation and framework for establishing design specifications for future systems.

- An integrated flight control system interactive sensor integration program (ISIP) was developed, demonstrated, and installed on the Air Force computer. This program addresses the sensor requirements of the flight control, guidance and navigation, and weapon delivery functions as directed interactively by the designer and the mission, the system configuration, cost, power, weight, volume constraints, and total system performance. The demonstration program contains performance, reliability, size, power, weight, cost data for gyros, accelerometers, radars, seekers, and air data systems in addition to analysis tools for evaluating navigation system accuracy, probability of target acquisition, and probability of kill for selected targets and weapons. Although only a subset of the integrated flight control problems, this program dramatically illustrates the capability of an interactive design technique and the payoffs of integrated control.

Despite a significant first step, many steps still remain to be undertaken to achieve a comprehensive integrated control design technique. The structure and the methodology have been formulated. The power of computer-aided design has been demonstrated. Additional efforts are required to apply the computer-aided ability to a larger part of the design structure and methodology. These efforts should attack two fronts. First, additional analysis techniques, particularly those addressing reliability/survivability, need to be exercised and refined with respect to computer-aided implementations. Second, the proof of the ultimate advantages of the integrated control design techniques and ultimately the value of integrated control resides largely in the span and quality of the data bases. It is recommended that the Air Force begin developing more comprehensive data bases built upon the sensor data base developed in the program.

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SECTION 1

INTRODUCTION

1.1 NEEDS AND OBJECTIVES

The need for integration of systems that aid or control the flight and missions of aircraft has existed since the invention of aircraft. As the aiding systems have become more sophisticated, the problem of integration has become more challenging. Today system integration requires the application of modern control theory to achieve the coordinated performance and simplified management desired for aircraft. Furthermore, these integration goals must be achieved while conforming to the significant and conflicting limitations that are being imposed on factors such as cost, size, weight, failure rates, availability, and vulnerability. It is only through top-down stagewise system development and the application of advanced system design principles and techniques that both the goals and constraints can be satisfied.

Integrated control is the mechanization that harmonizes the control of flight system and vehicle dynamics. During the research, management planning, and conceptual design of integrated control of flight (ICOF) systems, the time required for trade-off and evaluation studies of system concepts must be minimized. The level of design details investigated must be curtailed without unduly compromising the accuracy of the estimated performance and the physical and cost characteristics of the conceptual designs.

The objective of this study is to provide an appropriately efficient concept design methodology, to develop integrated control design techniques (ICDT) and to demonstrate their utility on ICOF conceptual design examples.

This document is the final report on the investigations and results of the ICDT project. The flow of the design methodology has been defined, the techniques required for implementation selected, and examples of the applications of the techniques have been illustrated.

The road map to complete the development of the ICDT methodology includes subsequent projects to develop the data banks required to support the design techniques and to develop the executive control program that would permit a systems engineer using an interactive computer-based approach to design and evaluate an ICOF system.

One example, showing the design process for an ICOF sensor set, was carried all the way through to an interactive design implementation and demonstration.

1.2 SEMANTICS AND SYNOPSIS

The shaping of the methodology flow to achieve an efficient and effective design process required the application of recently-conceived system design principles. These principles or approaches are listed in Table 1 along with the benefits they bring to system design. Descriptions of these design approaches are provided in the following paragraphs.

TABLE 1. APPROACHES TO SHAPING DESIGN METHODOLOGY THAT YIELD NEW BENEFITS FOR SYSTEM CONCEPT DEFINITION

Approaches	Benefits
Top-Level Design	• Concept definition level methodology convenient for research, development, and planning
Integrated-Control Design	• Reduced size and cost of system • Improved system effectiveness
Structured Design	• Design and integration guidelines showing "how to" as well as "what to"
Top-Down Design	• Mission/system performance requirements decomposed to component level to avoid design of performance optimized subsystems • System architecture driven by mission/system requirements
Computer-Aided Interactive Design	• Efficiency of design process--input and design data at fingertips

1.2.1 Top-Level Design

Top-level design refers to a system design process that develops the details of a design only far enough to provide for a reasonably accurate estimation of its cost and effectiveness characteristics. This process is appropriate for the program planning and concept definition stages of system development, as indicated in the system design morphology chart, Figure 1. It examines all the major trade-offs in system implementation and utility and defines the system architecture. The outputs of the process are system concept descriptions and development plans as used to generate requests for proposals (RFPs), planning documents, or type A and B (top-level) system and subsystem specifications.

Top-level design does not provide a sufficiently detailed description to begin the production and interfacing design of subsystem components. It does set the stage, however, for the detailed design process that leads to production.

1.2.2 Integrated Control Design

The objective of integrated control design is to develop a system having reduced size and complexity or improved performance, or both, relative to a system developed by direct integration of dedicated subsystem designs. The achievement of these integrated control design goals requires the application of some or all of the integrated design considerations described in Table 2. The objectives of each design approach considered are also indicated. The approaches apply to the integration of components, subsystems, and functions.

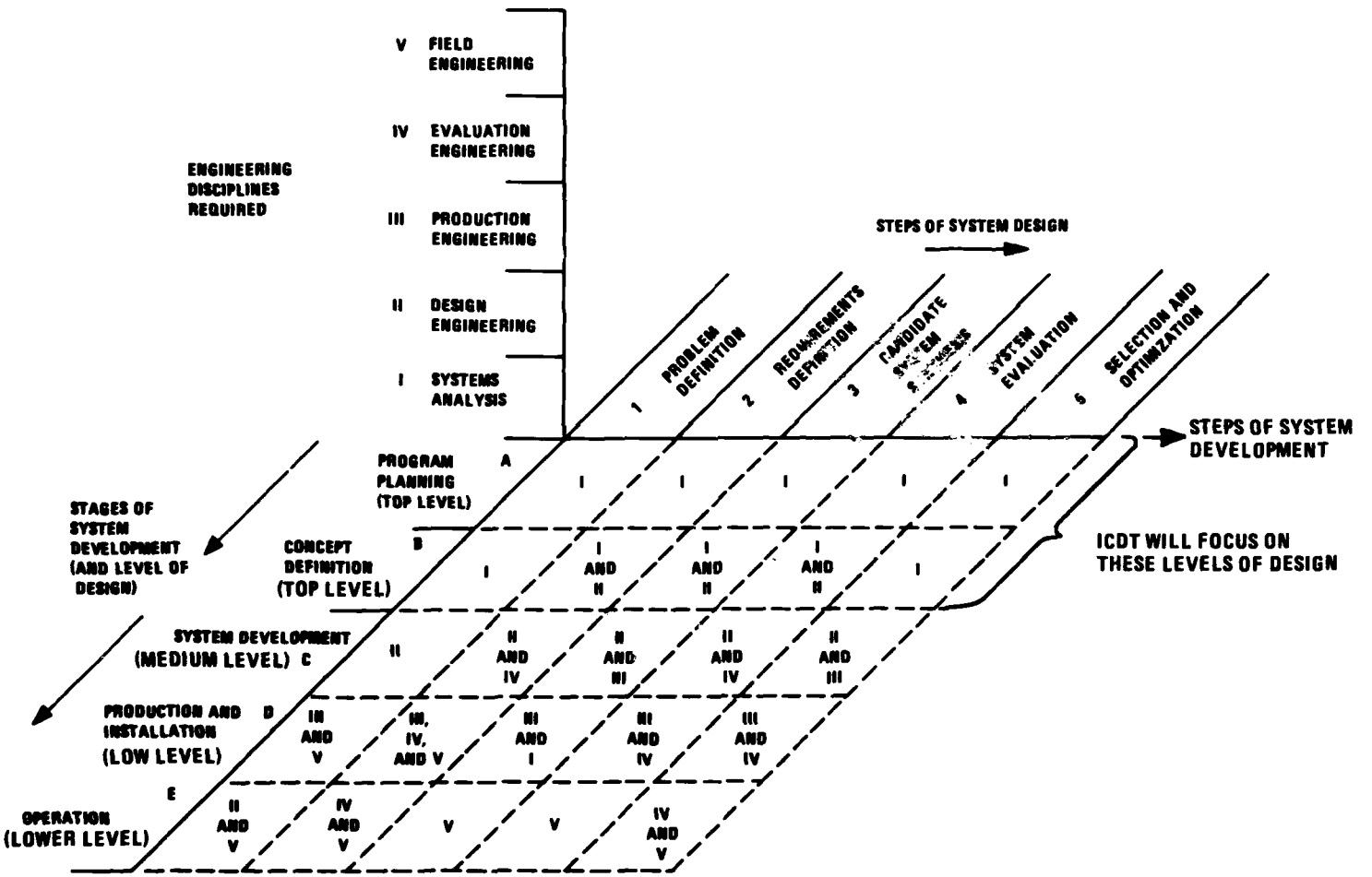
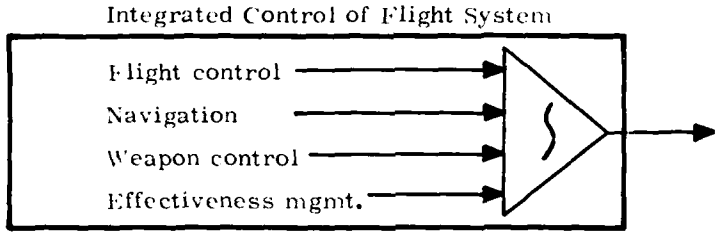


Figure 1. System Development Stages and Steps

TABLE 2. INTEGRATED CONTROL DESIGN APPROACHES

Approaches	Objectives
1. Subsystems integration to obtain a multi-function control system	Control to mission objective rather than subsystem optimization
2. Integration of basic sensing, data processing, or actuation functions	Eliminate redundant components
3. Integration of sensed data through filters to improve signal accuracy or information content	Improve signal accuracy and system performance
4. Integration by use of multi-function components	Reduce size and cost of components
5. Integration of processed subsystem signals to be sent to actuators	Simplify signal distribution and limiting



An indication of the functional differences between these two system integration approaches is presented in Figure 2. Integration of the sensing and processing functions for two of the subsystems is indicated. These integrations would likely lead to reductions in size and cost for the system designed through integrated control.

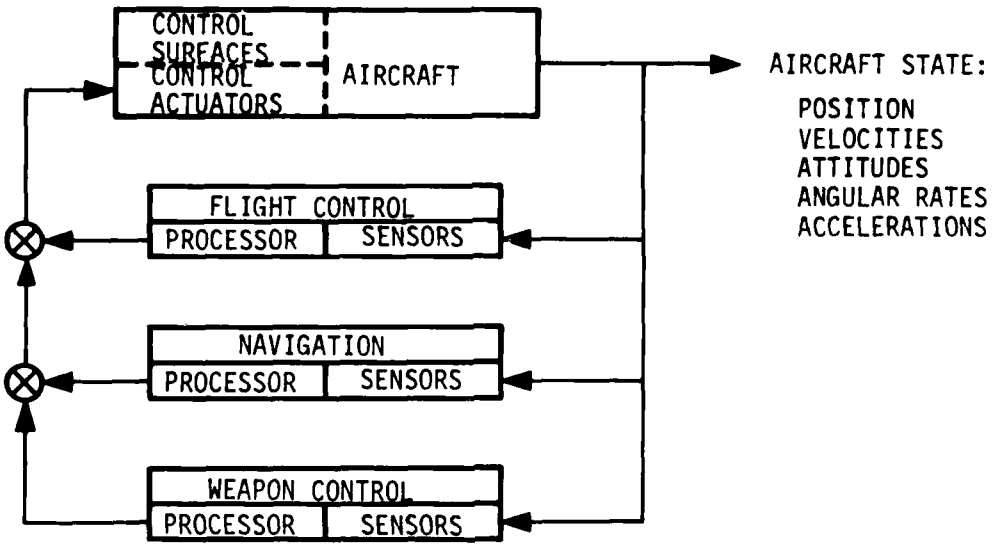
1.2.3 Structured Design

As used in this project, structured design refers to a design process in which each step is part of a carefully structured, logical, and orderly procedure. Structured design also implies a set of guidelines that describes how to do each step as well as what to do.

1.2.4 Top-Down Design

Top-down design is a structured design process that is started by decomposing the top-level system requirements, as they relate to mission goals, down to subsystem requirements and then to component-level requirements as shown in Figure 3. A system designed by meeting these component requirements is thus assured of meeting the top-level (mission/system) goals. In contrast, a bottom-up system design starts with the selection of components to meet traditional or specified subsystem requirements that are not derived from the specific mission goals. The system resulting from the integration of these components may be an overkill or an underkill when evaluated relative to the mission goals, and iterations of the design will be required.

A. INTEGRATION OF DEDICATED SUBSYSTEMS



B. INTEGRATED-CONTROL DESIGN

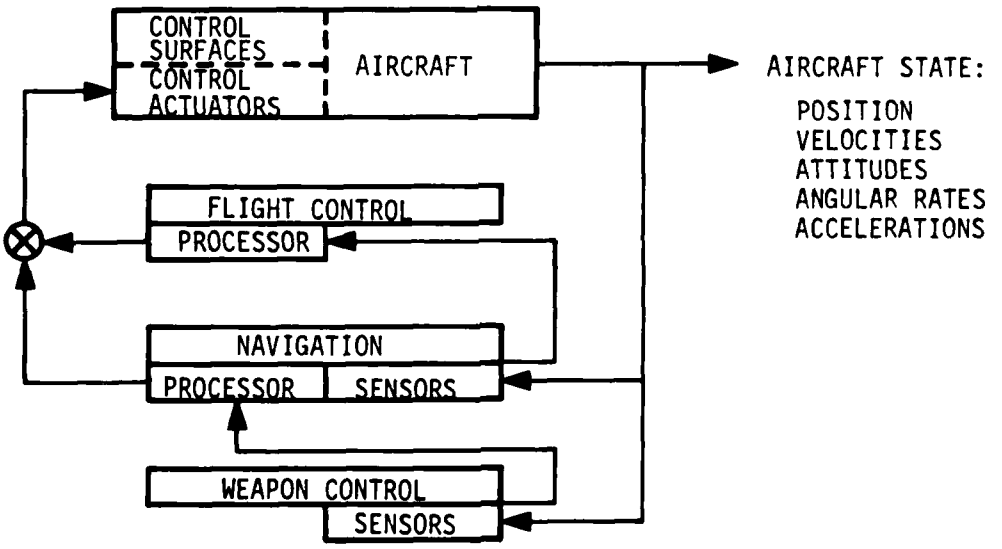


Figure 2. Contrast in System Design Approach

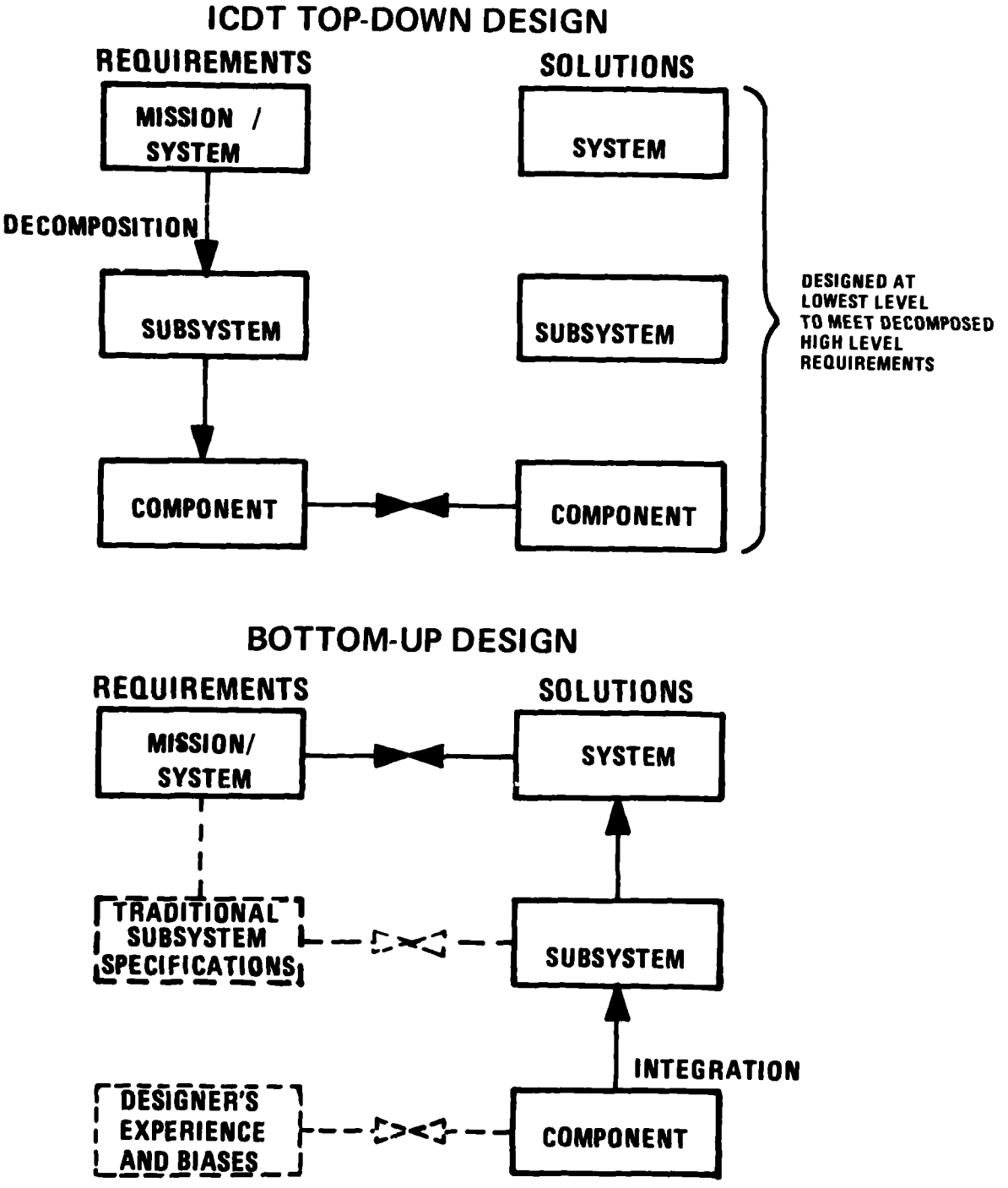


Figure 3. Contrasts Between Top-Down and Bottom-Up Design

Top-down design with its procedure of decomposition of requirements also provides a more equitable or unbiased allocation of functions between the data processing and non-data processing parts of the system and between the hardware and software than bottom-up design provides.

1.2.5 Computer-Aided Interactive Design

In addition to the usual meaning of this terminology (designer/methodology interaction implemented by an interactive graphics terminal and a man-machine oriented executive program), another dimension is added as it is applied to ICDT. The added meaning is compression of the design process from many participants using scattered resources to one individual interacting with a unified collection of techniques and data banks as shown in Figure 4. This design process contrasts in many ways with the present slower and costlier team-performed system concept definition illustrated in Figure 5. The present procedure requires many design specialists and their techniques and data banks in addition to the system engineer, who must interact with all of them repeatedly to accomplish the concept definition.

1.2.6 ICDT Demonstration Program

The overall objective of the demonstration program is to show that integrated control design techniques (ICDT) methodology is a viable approach and that it works. The demonstration program is a prelude to the large scale development of ICDT. The specific objectives of the demonstration program are:

- To focus attention on integrated sensor system design
- To develop specific algorithms for selection of sensor candidate sets

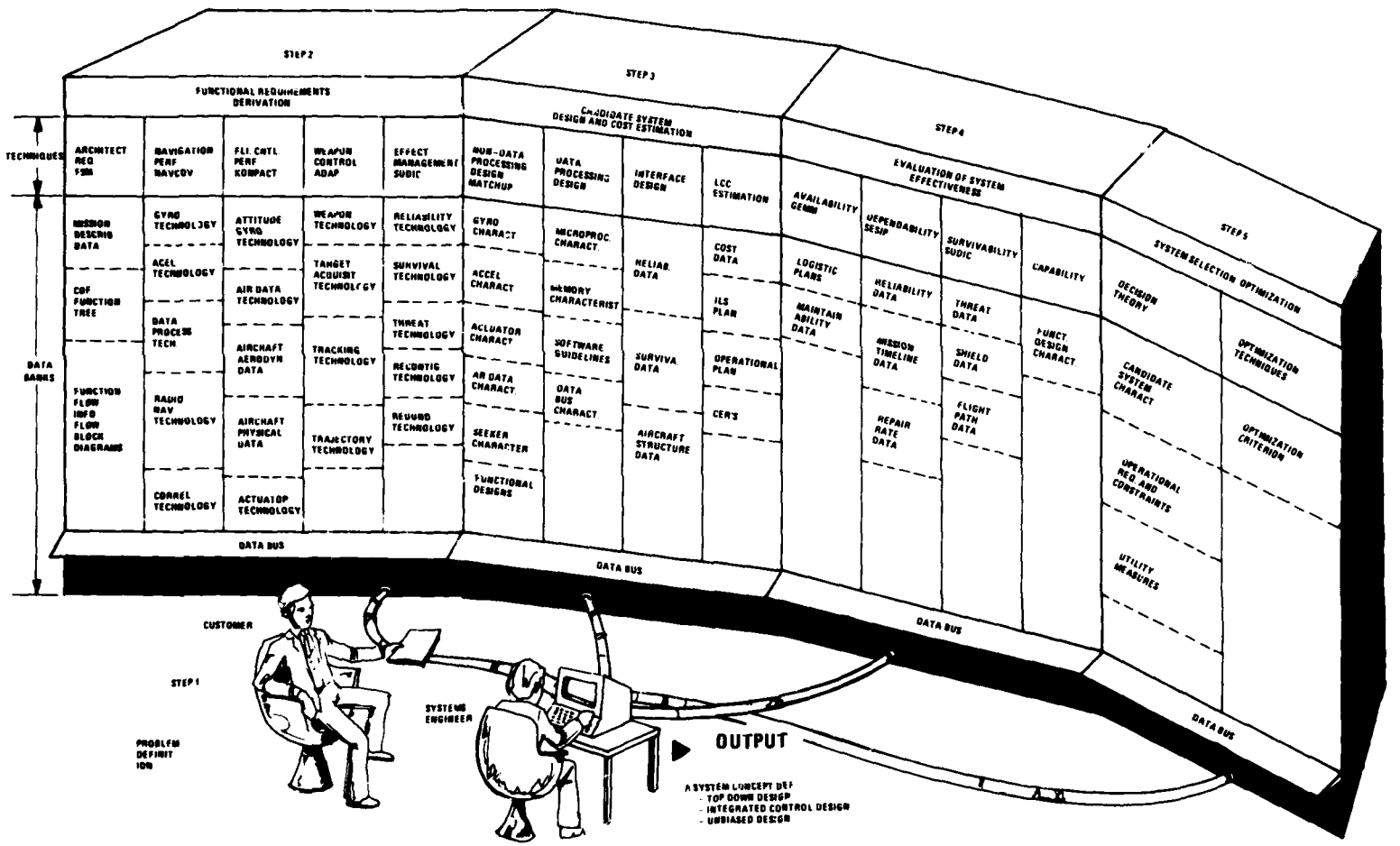


Figure 4. ICDT: The Interactive System Concept Definition Methodology "To Be"

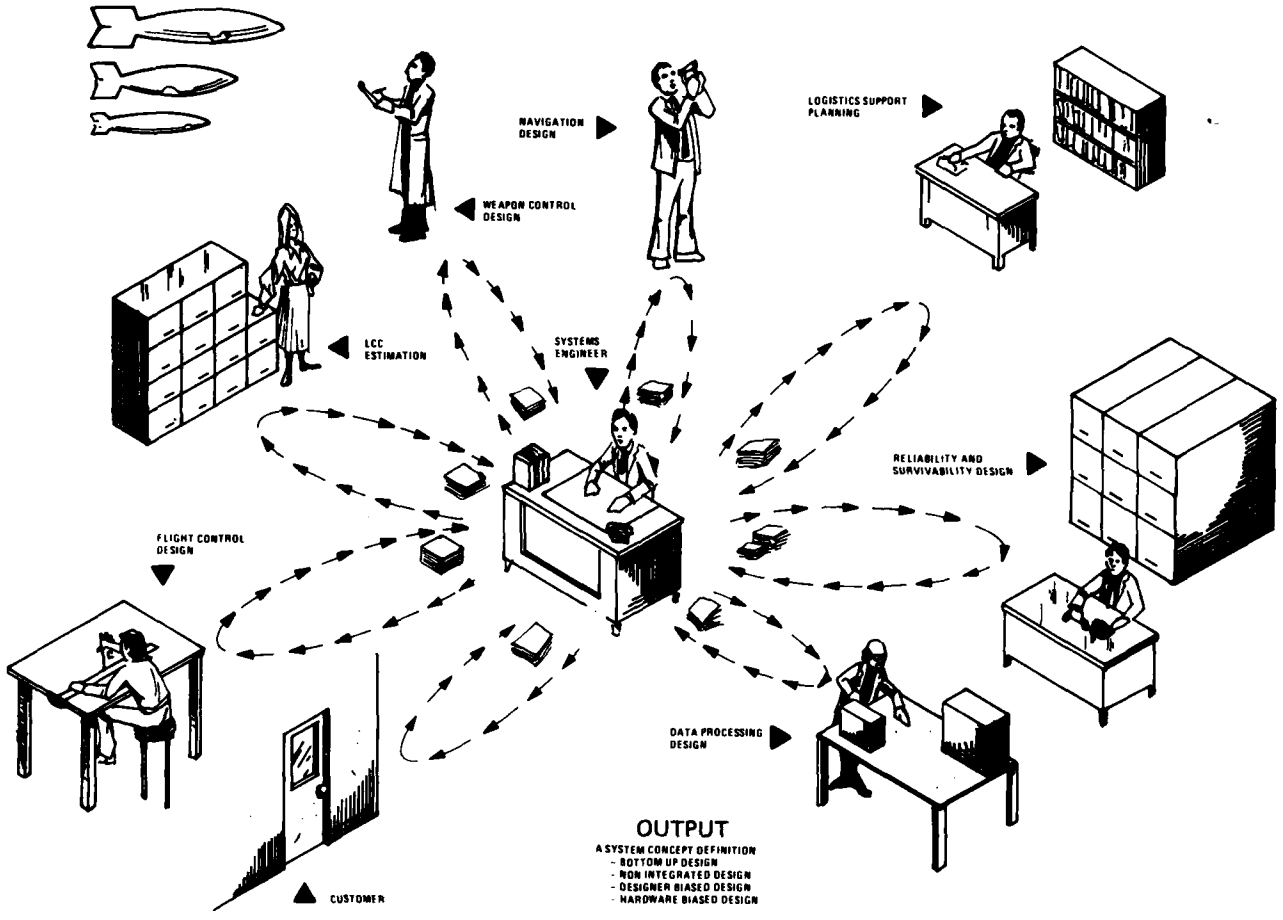


Figure 5. The System Concept Definition Process "As Is"

- To implement the algorithms on the interactive computer
- To develop a preliminary mission and sensor data base
- To demonstrate the integrated sensor set design

The integrated sensor set design process implemented on the interactive computer is illustrated in Figure 6. Simplified mission and sensor data bases are developed to demonstrate the design of integrated sensor sets. In the first step of the design process the required mission parameters (COF functions needed for the mission, the mission trajectory parameters, sensor requirements, etc.) are specified using the mission data base. In Step 2, the projected measurement requirements for the various COF functions are integrated to form projected measurement requirements for the mission. This data is used in Step 3 to generate candidate sensor sets with the help of the sensor data base. In Step 4, the navigation and weapon delivery performance is evaluated for the candidate sensor sets to check whether the required performance has been obtained. Optimization of the sensor set design is made by the designer in Step 5 to trade off performance against cost, weight, and other sensor characteristics.

In spite of the limited mission and sensor data base, the demonstration program has proved effective in designing integrated sensor sets to meet the specified mission requirements. In addition it has proved useful, in the simple designs generated by using the program, towards demonstrating the advantages of integrated vs nonintegrated sensor sets. The demonstration program is currently operational on the Honeywell and ASD computers. The description of the ICDT demonstration program and an illustrative example for integrated sensor set design are given in Section 4.0.

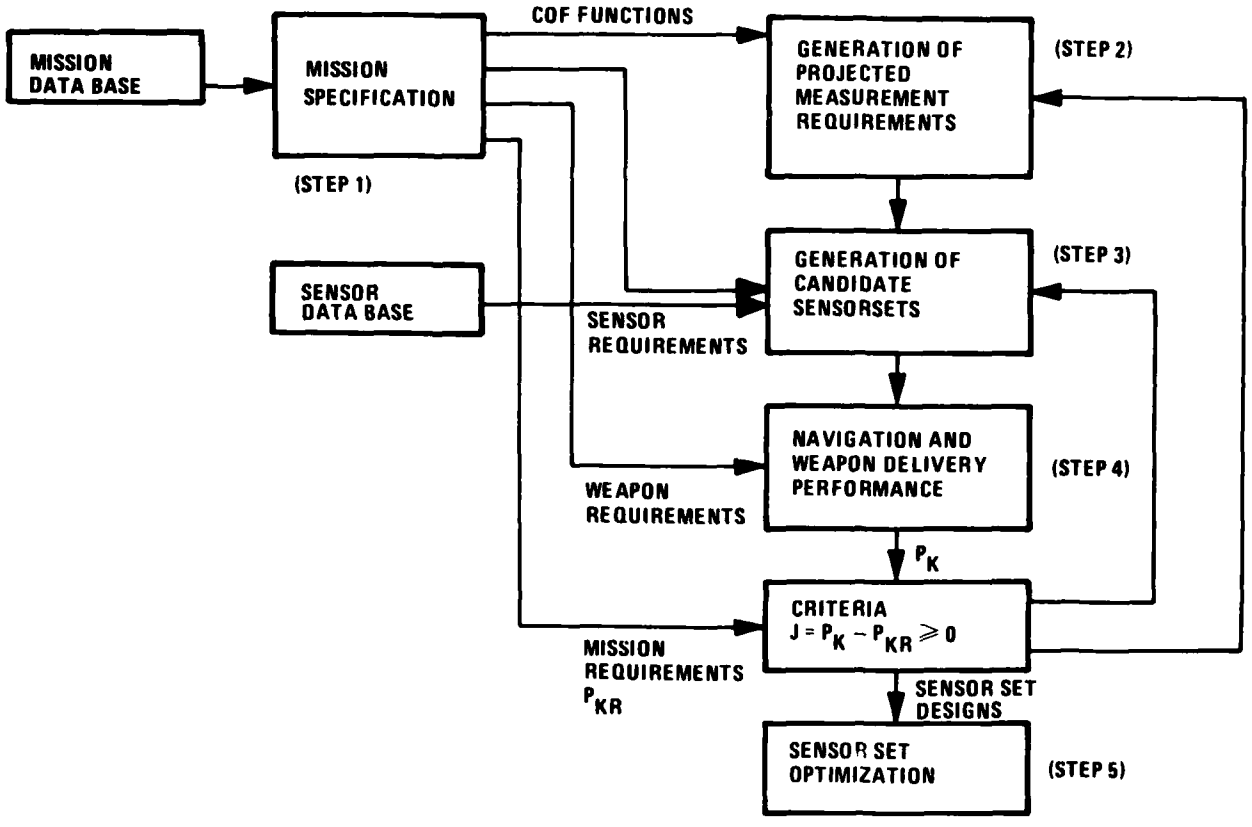


Figure 6. Integrated Sensor Set Design Process

SECTION 2

APPROACH

The development of the integrated control design (ICD) methodology flow and the collection of techniques required to implement the methodology were accomplished by performing the following set of tasks:

- Technology survey
- Methodology flow definition
- Selection of a technique for system effectiveness evaluation
- Collection, development, and correlation of system design techniques

The objective of each task is discussed below and the results are discussed in Section 3.

2.1 TECHNOLOGY SURVEY

The technology survey was undertaken to gather supplemental background and resource information on system design methodologies and on the

analytical techniques or models that might be applicable to integrated control design. The resulting references are listed below.[1-13]

---

[1] A.H. Agajanian, "A Bibliography on System Performance Evaluation," Computer, Vol. 8, No. 11, November 1975.

[2] Algirdas Avizienis, "Toward a Discipline of Reliable Computing," presented at IFIP Conference on Reliable Computing and Fault Tolerance in the 1980's, London, England, Sept. 26-29, 1979.

[3] John deS. Coutinho, Advanced Systems Development Management, New York: Wiley 1977.

[4] Gerald J. Hahn and Samuel S. Shapiro, Statistical Models in Engineering, New York: Wiley, 1967.

[5] K.C. Kaput and L.R. Lamberson, Reliability in Engineering Design, New York: Wiley, 1977.

[6] Melvin B. Kline, "Introduction to Systems Engineering: Lecture Notes," Monterey, CA: Naval Postgraduate School, 1979.

[7] _____, "Software and Hardware R&M: What Are the Differences?" Reprint presented at Reliability and Maintainability Symposium, San Francisco, CA, Jan. 22-24, 1981.

[8] Richard de Neufville and Joseph H. Stafford, Systems Analysis for Engineer and Managers, New York: McGraw-Hill, 1971.

[9] William D. Rowe, An Anatomy of Risk, New York: John Wiley, 1977.

[10] Andrew P. Sage, Methodology for Large Scale Systems, New York: McGraw Hill, 1977.

[11] Stanley M. Shinner, Techniques of System Engineering, New York: McGraw Hill, 1967.

[12] John H. Wensley, Leslie Lamport, Jack Goldberg, et al., "SIFT: Design and Analysis of a Fault-Tolerant Computer for Aircraft Control," Proceedings of the IEEE, Vol. 66, No. 10, October 1978.

[13] Ng Ying-Wah and Algirdas Avizienis, "ARIES 76 Users Guide," UCLA Eng. Rpt. 7894, Los Angeles, CA: Computer System Synthesis Group, School of Engineering and Applied Science, UCLA, Dec. 1978.

Major conclusions are:

1. No current or pending developments were found that were intended to provide a systems design methodology for integrated control of flight (ICOF) systems at the concept definition level of design.

2. Design techniques for control-of-flight systems exist in the literature, but they have been developed primarily for the detailed, full-scale stage of system design. These techniques need review and modification, such as simplification with respect to detail and upgrading with respect to data bank implementation in order to be applicable to the concept definition level of design and ICOF applications.

3. The design techniques available cover most of the techniques required for implementing the planned methodology.

4. Other than flight control and navigation system design techniques themselves, the most prolific and pertinent category of system design techniques found were those for digital data processing (DDP) subsystems. Highly structured and top-down requirements definition and system design techniques are being developed for these DDP subsystems and it is planned to adapt some of them to the ICDT design methodology.

2.2 METHODOLOGY FLOW DEFINITION

A generalized systems design methodology can be described in five or six classical steps.[14]

1. Problem definition
2. Functional requirements derivation
3. Candidate system design
4. Systems effectiveness evaluation
5. System selection/optimization

The development of a specific design process for ICDT required structuring these five major steps into substeps and selection of analytical design techniques for the substeps. The last four of the major steps require analytical techniques for developing the candidate system concepts and for evaluating their effectiveness and cost. These effectiveness and cost estimates then can be compared with the goals and constraints set in Step 1 for the factors involved. The analytical techniques have to be carefully selected to accommodate the desired scope of design parameters and the level of quantitative evaluation that matches the level of design detail desired. By constraining the overall design and evaluation methodology to a consistently top-level process, the time and cost goals required by program planning and concept definition were met.

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[14] Andrew P. Sage, "Editorial: A Case for a Standard for Systems Engineering Methodology," IEEE Transactions on Systems, Man, and Cybernetics, Vol. SMC-7, No. 7, 1977, pp. 499-504.

2.3 SYSTEM EFFECTIVENESS EVALUATION TECHNIQUES

2.3.1 Objective

The objective of this task was to define modeling techniques to be used for evaluating the effectiveness of candidate ICOF systems. This evaluation is required in Step 3 of the integrated control design methodology (ICDM) as a design implementation tool, as well as in Step 4.

2.3.2 Approach and Tasks

Methods for evaluating system effectiveness have been developed and used on many different programs. The most notable of these methods is the one defined by the Weapon System Effectiveness Industry Advisory Committee (WSEIAC). The committee reports[15] document their recommendations for a system effectiveness evaluation methodology and as such have provided the basis for most of the subsequent system effectiveness developments.

These methodologies were modified as necessary for the ICDT study. Specific considerations addressed include:

- Applicability to digital integrated control systems/design methodology

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[15] WSEIAC Task Group II, Prediction-Measurement: Summary, Conclusions, and Recommendations, Final Report, Vol. 1, AFSC-TR-65-2, Jan. 1965.

- New system design techniques--hardware and software
  --Reconfiguration and redundancy management
  --Fault isolation
  --Fault tolerance
- Pilot performance
- Model flexibility for growth/expansion (adding flight management features)
- Identifying inadequate areas of system design and design/cost drivers
  --Reliability
  --Maintainability
  --Mission performance
  --Cost

A system effectiveness evaluation methodology was defined to include the above considerations in the most efficient manner. This was accomplished by:

- Defining the detailed requirements for the ICDT effectiveness evaluation process
- Reviewing/evaluating existing models and techniques which would meet those requirements
- Selecting applicable techniques and/or defining modifications for application to the ICDM

2.4 TECHNIQUE SELECTION, DEVELOPMENT, AND CORRELATION

As indicated in the introduction, analytical techniques are required to accomplish the quantitative definitions and evaluations of the system candidates. These techniques implement the last four major steps of the methodology flow. They were selected to accommodate the ICDT methodology objectives by screening them against these constraints:

- Input and output parameters must be consistent with those available during the concept definition stage of design.
- Techniques must be closed-ended to meet economy and efficiency goals of top-level design.

The techniques recommended are identified in terms of the models they employ. The details are given in Section 3.0.

SECTION 3

SYSTEM METHODOLOGY RESULTS

This section presents the results of the ICDT total systems approach methodology development. The five major steps in an integrated control-of-flight system design are presented together with the analytical methods selected to implement them.

3.1 METHODOLOGY FLOW

The five steps in the methodology flow and the outputs of each step that serve as inputs to the next step are shown in Figure 7. These steps are shown as sequential although iterations may occur at any point in the process where goals or constraints are not satisfied.

As indicated previously, steps 2 through 5 use analytic quantitative modeling of the system and its dynamics and require analytical techniques for their execution. Step 1, on the other hand, is a data collection process and does not depend on analytical techniques. This step can be greatly aided by an outline that formalizes the dialogue needed to produce detailed descriptions of the problem and of the resources to be applied to its solution.

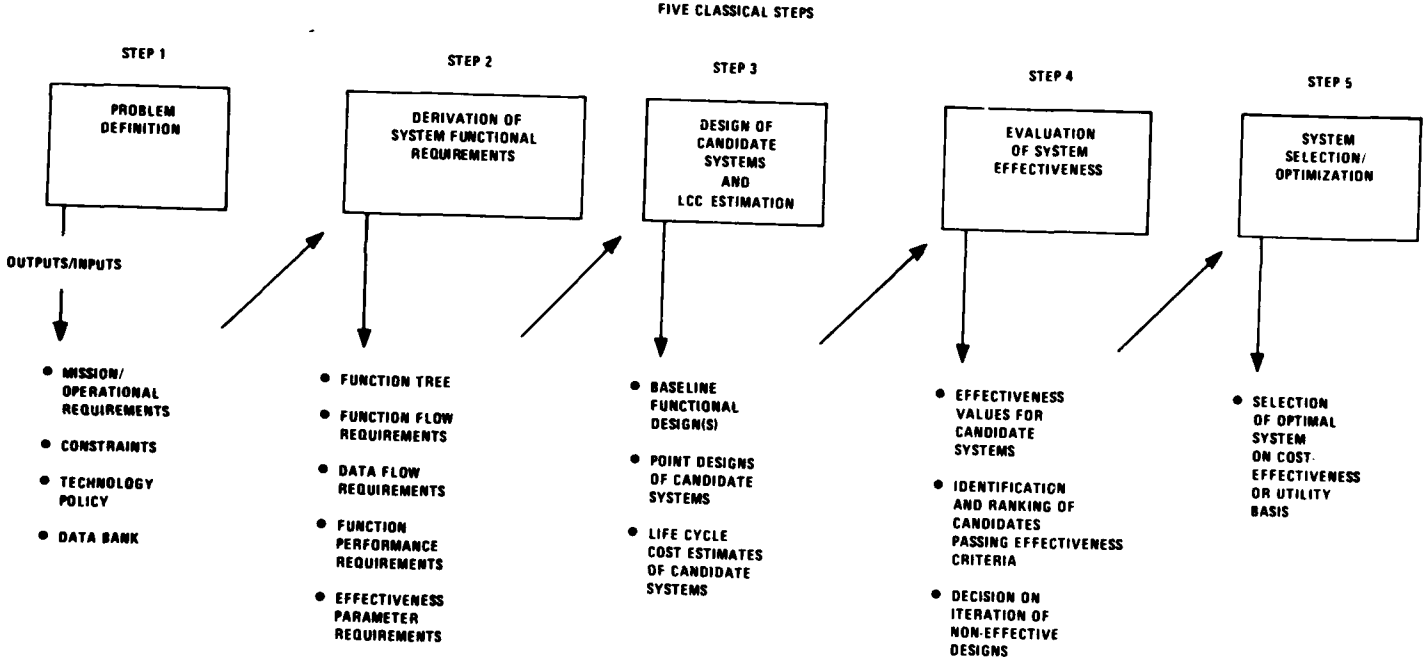


Figure 7. Methodology for ICDT

As far as the substeps within the major steps of the flow are concerned, steps 1, 2, 4, and 5 are fairly straightforward and need no further description relative to the methodology flow at this point. These steps will be discussed more fully later.

On the other hand, step 3, covering the design of candidate systems and an estimation of their life-cycle costs, has some substeps, branchings, and potential iterations of the flow that warrant discussion at this time. An expanded view of step 3 is presented in Figure 8.

The input to step 3 is the system functional architecture and requirements derived in step 2. For each functional architecture to be pursued, these requirements may be considered as a functional design if the performance requirements have been reduced to point values rather than sets of ranges of acceptable values. This input includes functional performance requirements for each operational function (subsystem), subfunction, and mode. It also includes block diagrams for each subsystem that show the control and data flow requirements.

Within step 3 the first task is to allocate the functions to be performed by each subsystem into the basic categories of sensing, data processing, and actuation. A limited degree of functional integration may be accomplished at this time by looking across each of the subsystems for redundant or highly similar functions that can be integrated.

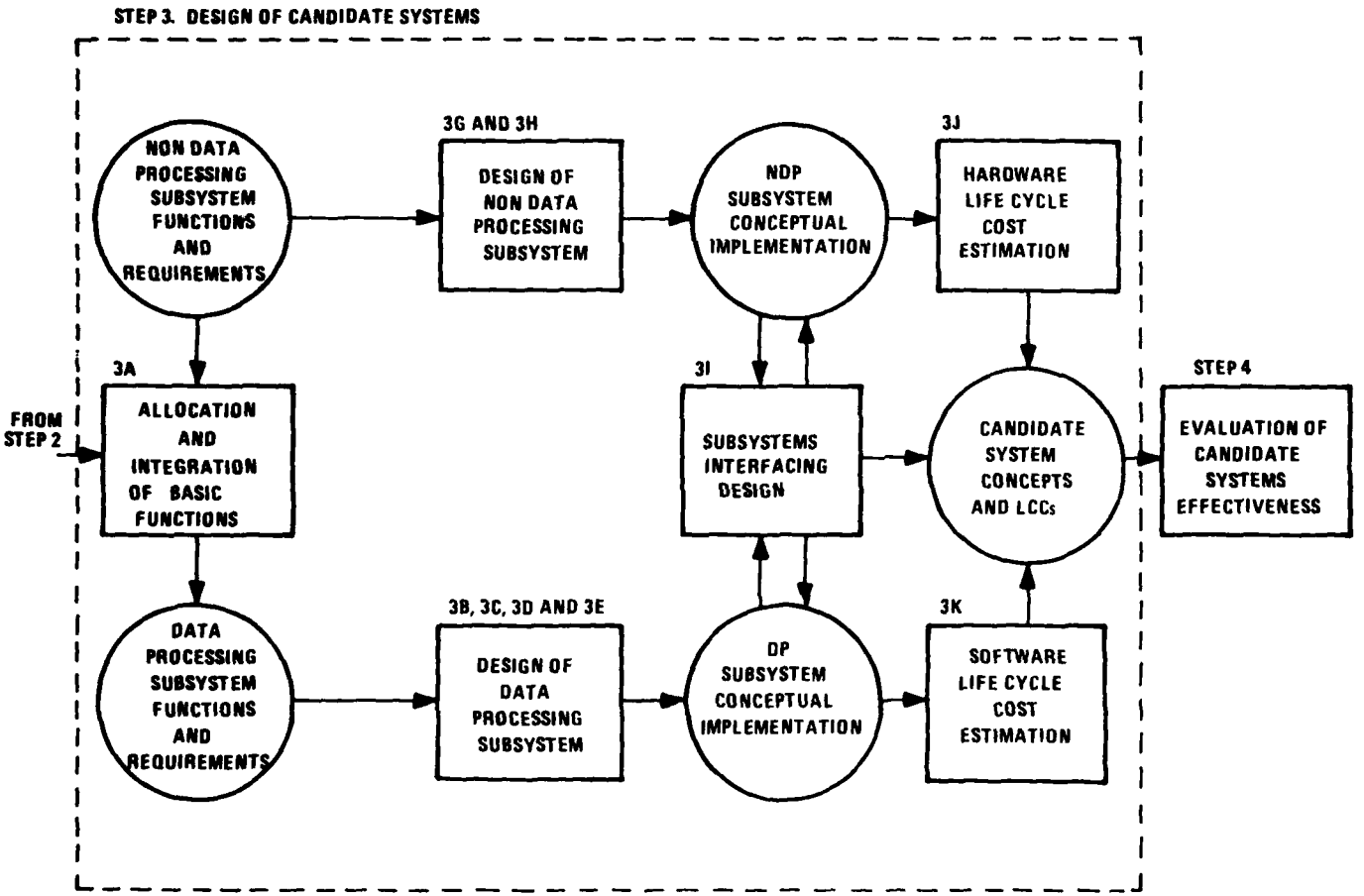


Figure 8. Expansion on Methodology for Step 3

The next task is to combine the sensing and actuating functions into a non-data processing subsystem category for implementation by a hardware type of design methodology. The data processing subsystem that remains is implemented by a distinctly different hardware/software design methodology. The hardware/software nature of the data processing subsystem requires a further branching of the methodology flow as shown in Figure 9.

At this point in the methodology flow, the system concept is essentially an unintegrated one in the sense that the interfacing of the sensors, actuators, and data processing components has not been addressed. This interfacing design, substep (3i), must involve consideration of reliability, maintainability, and survivability as well as capability. Overall system goals will be set for these four attributes during the problem definition. During the functional design process, however, only the capability (performance) goals are decomposed to the component level. In order to develop and satisfy some subsystem- and component-level goals for the other attributes, a two- or three-stage iteration of the interfacing design substep is recommended. The first stage would be to consider a single-thread interfacing of the components selected for the non-data processing and data processing subsystems. Analyses to determine the values of reliability, maintainability, and survivability are then carried out for the single-thread system and for a correspondingly simple baseline maintenance plan. The values calculated are compared with the system values established during problem definition. The differences can be used as goals for the second stage of the interfacing design step. The second stage would evaluate the use of redundancy of the components and their links for improving reliability and survivability. Geometrical separation, reconfigurability, and shielding

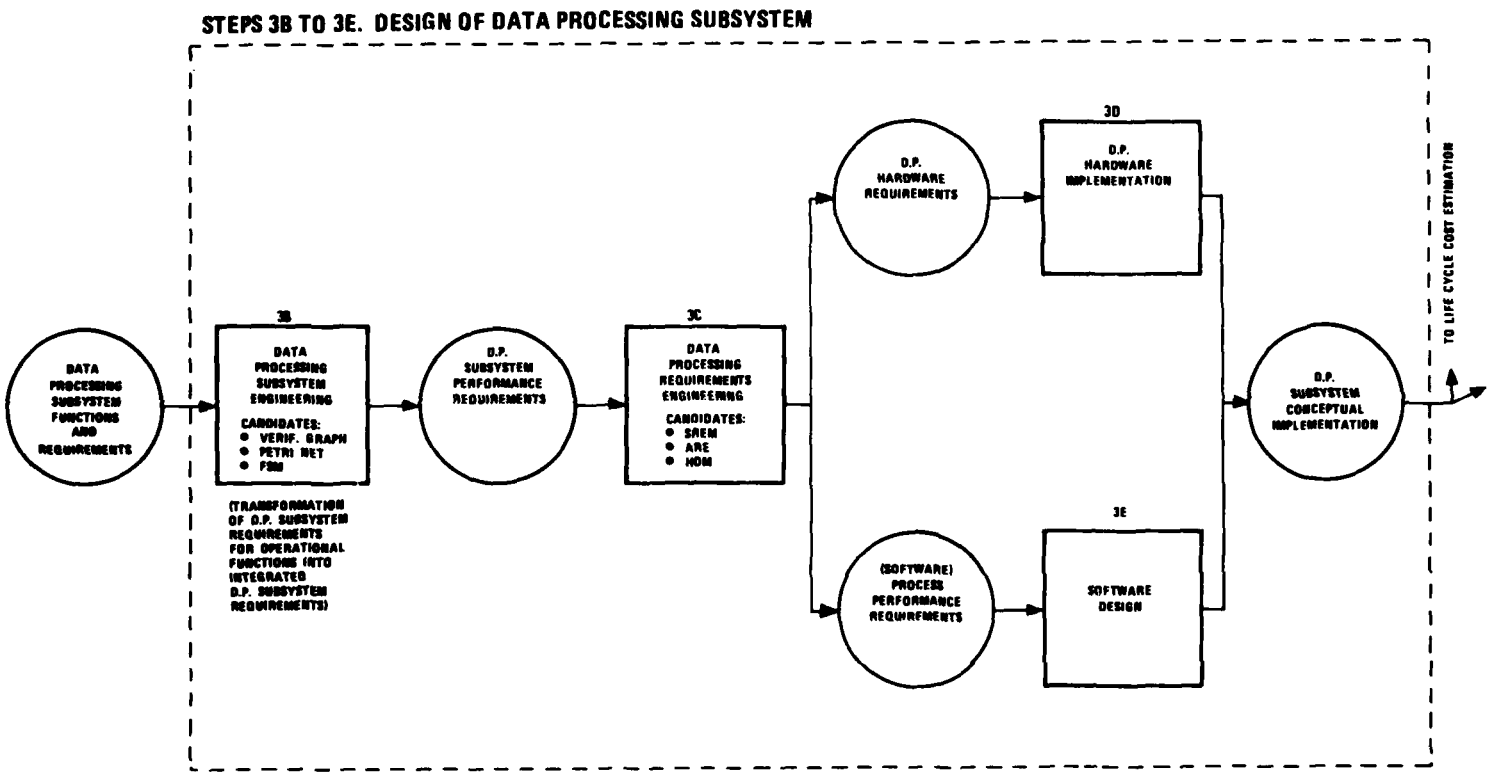


Figure 9. Expansion on Methodology for Data Processing Subsystem Design

would be applied to improve survivability. The second stage would also consider built-in test provisions plus a modified maintenance plan for improving maintainability. An analysis of the second stage system would then show whether the goals set during problem definition were met. If not, a third iteration would be necessary to fine tune the interfacing design and meet the system goals.

To complete the conceptual design of the candidate system, hardware and software life-cycle cost (LCC) estimations are made. The system is then sufficiently defined to proceed with the effectiveness evaluation, step 4, and the cost-effectiveness optimization/selection, step 5.

3.2 PROBLEM DEFINITION

In Step 1, problem definition, integrated flight control system mission, requirements, constraints, operating policies, schedules, technology availabilities, and any additional major design driver must be precisely defined and structured so that meaningful design trade-offs can be executed. An example of the topics covered by the problem definition is given in Table 3.

The topics illustrated in Table 3 apply to the design of ICOF systems for military aircraft having either air-to-ground or air-to-air combat missions. Furthermore, the ICOF systems covered by this methodology include the following specific subsystems:

- Flight control
- Navigation

TABLE 3. TOPICS COVERED BY PROBLEM DEFINITION

1.	Mission	Tactical Air Warfare	
2.	Mission Area	Interdiction	
3.	Mission Need	Control-of-Flight System for FX	
4.	Mission Segments	a. Take-off b. Climb c. Cruise d. Penetrate e. Detect/Acquire Target	f. Attack g. Assess/Depart h. Return i. Approach/Land
5.	COF Functions Required	a. Flight Control b. Navigation	c. Weapon Delivery d. Effectiveness Management
6.	System Goals	a. Effectiveness = .95 b. Cost = $200K per unit = $3M LCC	
7.	Constraints	a. Effectiveness > .90 b. Cost < $250K per unit < $5M LCC c. Physical size < 2.0 cu. ft. weight < 80 lbs.	d. Interfacing Required • Pilot • A/C Eq. of Motion • Control Actuators • A/C Subsystems BITE e. Interoperability • None specified
8.	Technology Policy	a. No technology restrictions	b. I.O.C. = 1985
9.	Logistics Policy	a. GEMM Model Policy No. 4	

- Weapon Control
- Effectiveness management

3.3 DERIVATION OF FUNCTIONAL REQUIREMENTS

The functional requirements obtained from step 2 are described as the functional architecture desired plus the functional performance, control flow, and data flow characteristics developed for the system. If specific values of the latter characteristics are established from the derived sets of acceptable ranges of the characteristics, the requirements become those for a specific functional design corresponding to the architecture.

No decomposition of the values of the dependability, maintainability, or survivability requirements from the system level specified in the problem definition to the subsystem and component levels is attempted in this step. System capability, however, is decomposed into performance requirements at the subsystem and component levels by the analytical techniques to be described. The processes for achieving the other system-level effectiveness goals are part of the implementation design methodology of step 3.

3.3.1 The Structuring of the Functional Architecture

The structuring of the functional architecture starts with the decomposition of the mission phases into segments and events and the establishment of a time line. The system functions prescribed in the problem definition are then decomposed into subfunctions and modes. By correlating the mission

segments and subsystem modes, a set of fully operational subsystem and system states can be established. Next, a system state transition matrix (the fully operational system states vs causal events), referred to as the description of a finite state machine (FSM), is generated. The FSM description is the key to developing the display and control subsystems interface requirements with the four subsystems included in the ICDT design methodology. The FSM description is also needed to establish the event and information flow requirements to be handled in part by the data processing subsystem and in part by the pilot through his controls.

From the FSM description, the transitions of the fully operational states during the events associated with the mission time line can be charted. This time line forms the baseline for the subsequent degraded and failed state analyses required to determine the system's dependability, maintainability, and survivability.

The system descriptors derived in this process can also be used to generate the top-level functional block diagram of the system which is the primary representation of the system's functional architecture.

The substeps of the structuring of the functional architecture just described are summarized in Table 4 and an instructive example of how they are accomplished and the parameters they encompass is given in the next subsection.

TABLE 4. THE SUBSTEPS FOR FUNCTIONAL ARCHITECTURE STRUCTURING

1. Mission and System Review and Extended Description
   - Phases
   - Functions
   - Functional partitioning
   - Constraints
2. System Functional Description and Mission Phase Decomposition

Functions	Phases
Subfunctions	Subphases
Modes	Segments

3. Correlation of Mission Segments and System Modes
   - Segments and system modes → System states (fully operational)
4. Finite State Machine (FSM) Generation
   - Function state transition matrix
   - (System states vs events)
5. System States vs Mission Timeline
6. Top-Level Functional Block Diagram of System
   - Functional interfaces
   - Information flow

3.3.1.1 Illustrative Example of Functional Architecture Structuring--

3.3.1.1.1 Mission and System Definitions from Step 1--In Step 1, the problem definition, the illustrative example established that the system to be conceptually designed is a control of flight (COF) system for an existing (or fully designed) FX airplane and that the COF system is to provide:

- A flight control function
- A navigation function
- A weapon delivery function
- An effectiveness management function

The FX (fighter) airplane mission consisted of these phases:

1. Take-off
2. Climb
3. Cruise
4. Penetrate
5. Detect/acquire/attack target
6. Assess/depart
7. Return
8. Approach/land

For this illustrative/instructive example the focus will be on the critical number 5 phase, detect/acquire/attack target.

The design of the FX airplane is assumed to be complete enough that these interface requirements and constraints have been placed on the design of the COF system:

- The aircraft control surfaces are designed and their characteristics defined.
- The control surface actuators are designed.
- The cockpit displays and controls are designed except for the autopilot control panel and the COF-related panels, which will be completed after the COF design has defined the flight control, navigation, weapon control, and effectiveness management subsystem characteristics and interfacing requirements.

The functional partitioning just described between the aircraft and the COF system is illustrated for the flight control function in Figure 10.

3.3.1.1.2 System Functional Decomposition--Starting with the four COF functions required, decisions must be made on the array of sub-functions and modes that will be needed to achieve the desired functional performance characteristics. For this example the functional decomposition shown in Figure 11 was developed.

A more detailed definition of the mission phases is also required for the functional design development. These details can be obtained by breaking the mission phases into subphases and segments as shown in Table 5 for the detect/acquire/attack target phase of the mission.

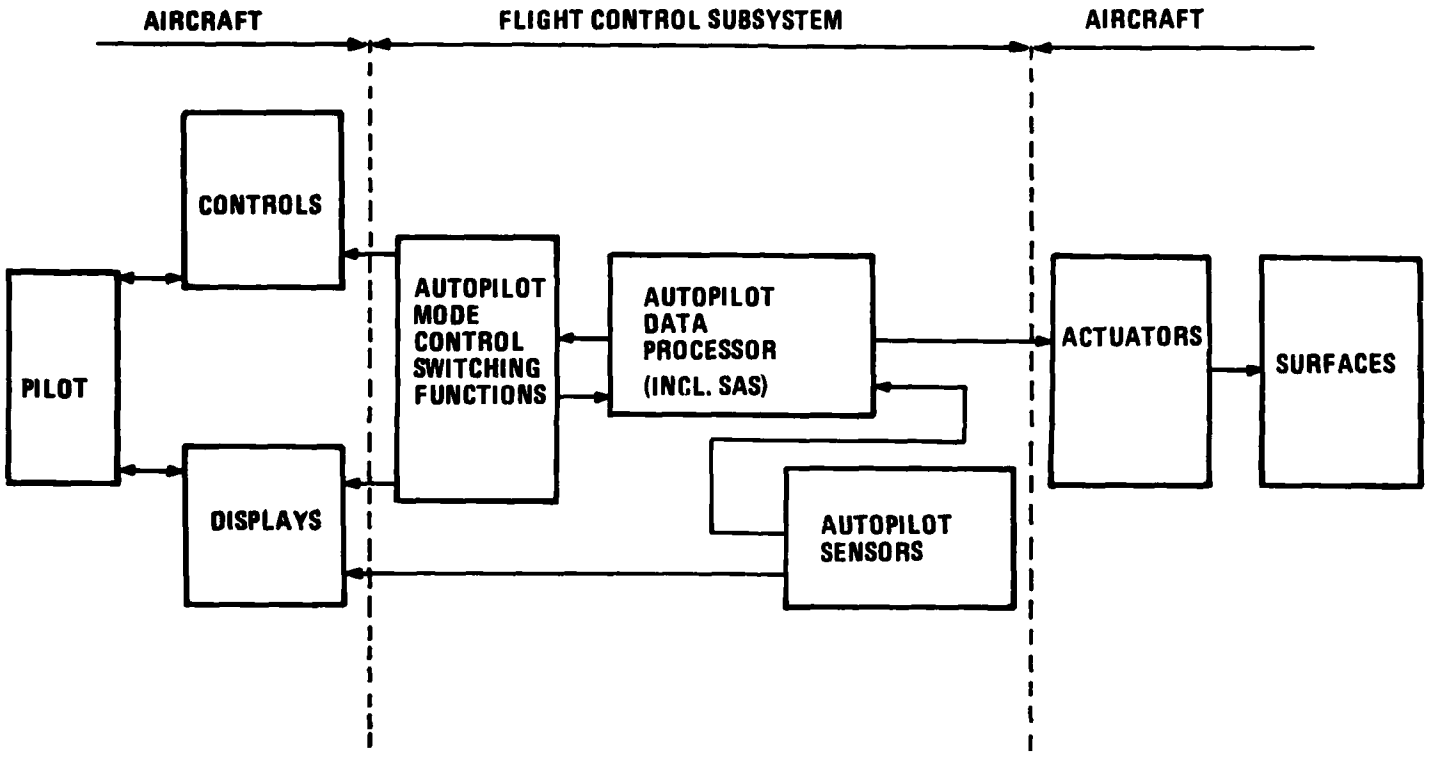


Figure 10. Flight Control/Aircraft Functional Partitioning

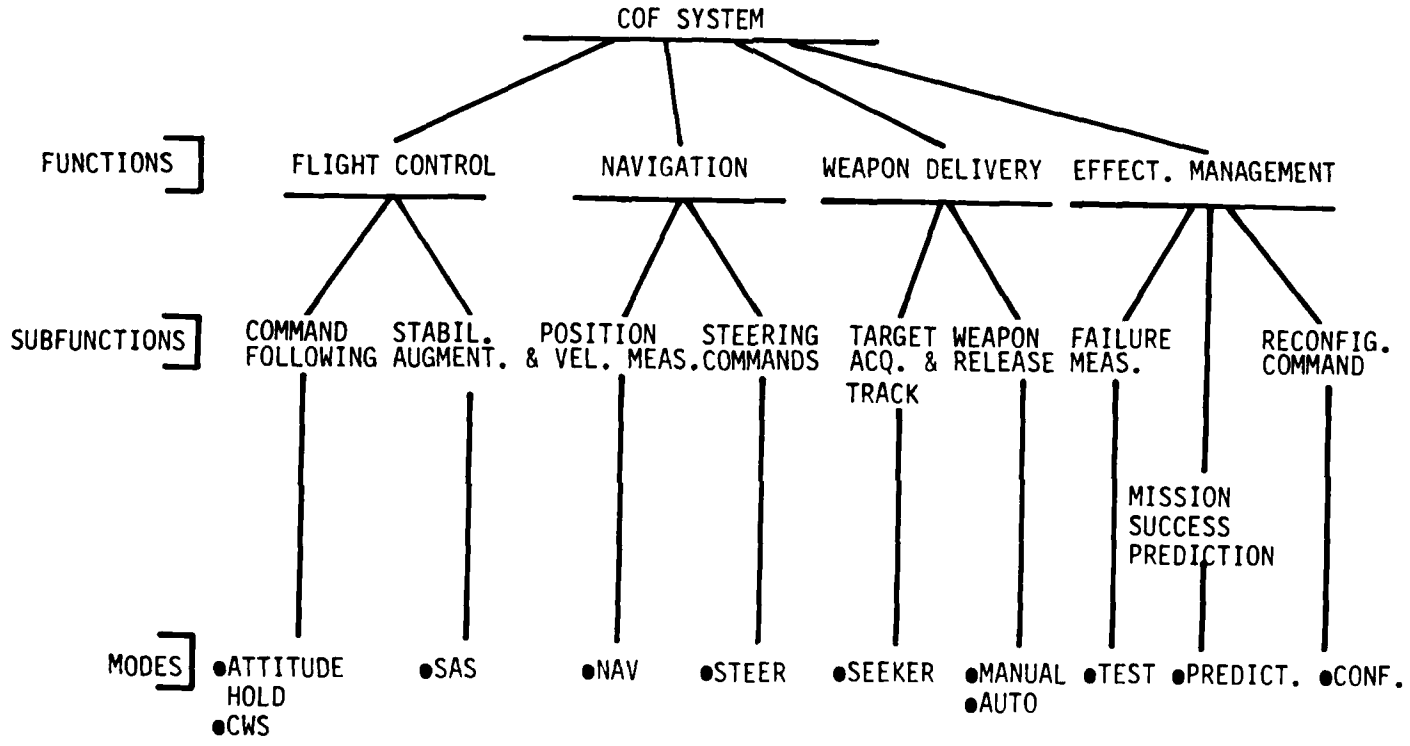


Figure 11. Decomposition of COF System Functions

TABLE 5. DECOMPOSITION OF MISSION PHASE NUMBER 5

	Detect	Acquire	Attack
Subphases	1. Straight and level flight	2. Dive for acquisition	3. Attack target
Segments	a. Transition to straight and level flight	a. Hold straight and level flight	a. Hold flight path
	b. Hold straight and level flight	b. Pitch over to dive path	b. Track target
		c. Acquire target	c. Transition to pull-up
		d. Hold flight path	d. Exit
		e. Exit (to straight and level)	

3.3.1.1.3 Correlation of Mission Segments and System Modes--The next substep is to define the COF system operational states through the correlation of mission segments and COF modes. This correlation is shown in Table 6 for subphase 2 of mission phase 5.

For this mission phase and subphase we can identify the following operational states for each COF function (subsystem):

- Flight Control States
  - I Attitude hold on; CWS off; SAS on (segments a and d)
  - II Attitude hold off; CWS on; SAS on (segments b, c, and e)
- Navigation States
  - I Navigate on; steering off (all segments)

TABLE 6. SEGMENTS/MODES CORRELATION TABLE

Subphase 2 Mission Segments	COF Modes: Attitude Hold	CWS	SAS	Navigation	Steer	Seeker	Manual	Automatic	Test	Predict	Configure
a. Hold straight and level flight	X		X	X					X	X	X
b. Pitch over to dive path		X	X	X		X			X	X	X
c. Acquire target		X	X	X		X			X	X	X
d. Hold flight path	X		X	X		X			X	X	X
e. Exit		X	X	X					X	X	X
	Flight Control			Navigation		Weapon Delivery			Effectiveness Management		

- Weapon Delivery States
  - I Seeker off; manual off; automatic off (segments a and e)
  - II Seeker on; manual off; automatic off (segments b, c, and d)
- Effectiveness Management States
  - I Test on; prediction on; configure on (all segments)

When all of the mission phases, subphases, and segments are analyzed in this manner, additional subsystem operational states will occur and some of the above states will reoccur.

3.3.1.1.4 Finite State Machine (FSM) Generation--The FSM[16] is a state transition matrix which represents the pilot-generated and external events that cause the subsystem state transitions. This matrix is developed by first identifying the events that cause the transitions between mission segments as shown in the following illustration for the flight control subsystem for subphase 2 of mission phase 5.

Then by correlating Tables 6 and 7 with the flight control subsystem state definitions, the FSM matrix illustrated in Table 8 can be developed.

TABLE 7. MATRIX DEFINING SEGMENT TRANSITIONS CAUSED BY EVENTS

	Events			
Subphase 2 Mission Segments	Pilot Pushes CW	Pilot Turns on Seeker	Pilot Releases CW	Pilot Aborts Attack
a. Hold straight and level flight	b	-	-	-
b. Pitch over to dive angle	-	c	d	e
c. Acquire target	-	-	-	e
d. Hold flight path	-	-	-	e
e. Exit	-	-	-	-

[16] J.E. Hopcroft and J.D. Ullman, Introduction to Automata Theory, Languages, and Computation, Reading, Massachusetts: Addison-Wesley Publishing Co., 1979.

TABLE 8. THE FSM MATRIX FOR FLIGHT CONTROL DURING SUBPHASE 2 OF PHASE 5

Subphase 2 Mission Segments	Events			
	Pilot Pushes CW	Pilot Turns on Seeker	Pilot Releases CW	Pilot Aborts Attack
I Attitude hold on; CWS off; SAS on	II	-	-	II
II Attitude hold off; CWS on; SAS on	-	-	I	-

For clarity in discussing the subsequent steps in the functional requirements definition process, the substeps for developing an FSM matrix for subphase 3 of mission phase 5 will be illustrated and used. The subphase 3 segments and COF modes correlation in Table 9 is developed from Figure 11 and Table 5.

The flight control subsystem operational modes for subphase 3 then can be defined as:

I. Attitude hold on; CWS off; SAS on (segment a)
II. Attitude hold off; CWS on; SAS on (segments c and d)
III. Attitude hold off; CWS off; SAS on (segment b)

TABLE 9. SEGMENTS VS MODES CORRELATION TABLE FOR SUBPHASE 3

Subphase 3 Mission Segments	COF Modes: Attitude Hold	CWS	SAS	Navigation	Steer	Seeker	Manual	Automatic	Test	Predict	Configure
a. Hold flight path	x		x	x		x			x	x	x
b. Track target			x	x	x	x		x	x	x	x
c. Transition to pull-up		x	x	x					x	x	x
d. Exit		x	x	x					x	x	x
	Flight Control			Naviga-tion		Weapon Delivery			Effectiveness Management		

The matrix showing the mission segment transitions caused by events is shown in Table 10.

TABLE 10. SUBPHASE 3 SEGMENTS VS PILOT- OR ENVIRONMENT-INDUCED EVENTS

Subphase 3 Mission Segments	Events: Pilot Turns on Auto Steering Weapon Release	Pilot Notes Release of Weapon	Pilot Aborts Attack	Pilot Pulls Back on Stick
a. Hold flight path	b	-	d	c
b. Track target	-	c	d	c
c. Transition to pull-up	-	-	d	-
d. Exit	-	-	-	-

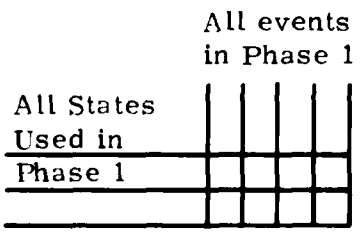
The FSM matrix for subphase 3 is shown in Table 11.

TABLE 11. FSM MATRIX FOR PHASE 5, SUBPHASE 3

Subphase 3 Flight Control States	Pilot Turns on Auto Steering Weapon Release	Pilot Notes Release of Weapon	Pilot Aborts Attack	Pilot Pulls Back on Stick	
I Attitude hold on; CWS off; SAS on	III	II	II	II	
II Attitude hold off; CWS on; SAS on	-	-	-	-	
III Attitude hold off; CWS off; SAS on	-	II	II	II	

3.3.1.1.5 System States vs Mission Time Line--When the entire set of FSM matrixes for all the mission phases and subphases has been constructed, a tabulation of them can be made for each COF subsystem as shown for the flight control subsystem in Table 12.

By combining the FSMs columwise, a composite FSM for each mission phase can be obtained that will resemble these sketches:



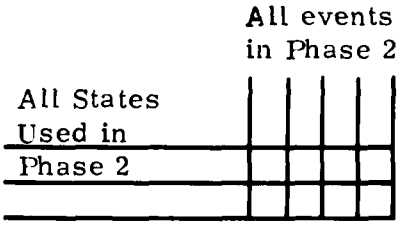


TABLE 12. TABULATION OF FSMs FOR FLIGHT CONTROL

	Mission Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8
Subphase 1								
2					FSM 5,2 FC States Events			
3					FSM 5,3			
4								
X								

Then by combining across the phases, a composite flight control FSM matrix for the whole mission can be obtained. An example is shown in Table 13.

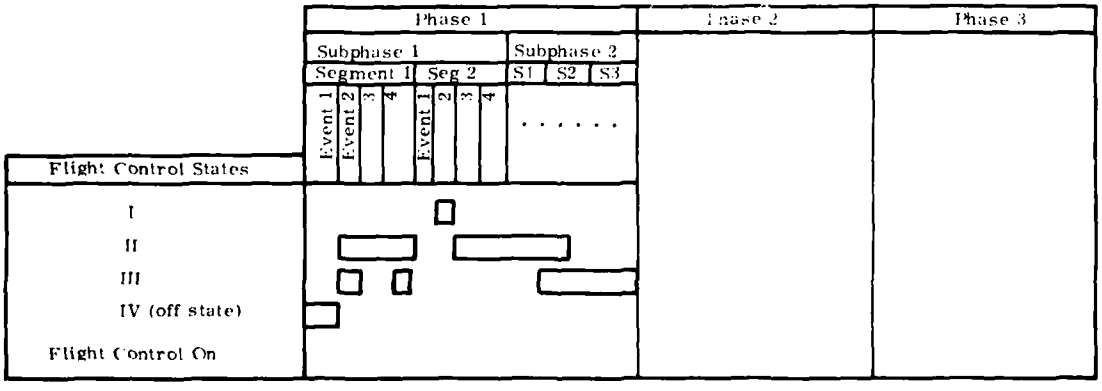
Since the events are defined for the mission segments and subphases and, therefore, for the phases, a mission time line for the flight control states can easily be developed. An example is shown in Table 14.

3.3.1.1.6 Top-Level Functional Architecture of System--By following the process just described for the navigation, weapon delivery, and effectiveness management functions, the mission time lines for each of these subsystems can be developed. These time line vs operational state diagrams and the information generated during their development are the functional

TABLE 13. THE COMPOSITE FLIGHT CONTROL FSM FOR THE WHOLE MISSION

	All pilot or external events for Mission				
All Mission Flight Control States	Pilot switches on power to autopilot	Pilot selects autopilot mode for takeoff	Pilot transitions to straight & level for cruise	Pilot turns on auto steering and weapon release	Pilot notes touchdown
I. Attitude Hold On; CWS Off; SAS on	-	-	-	III	-
II. Attitude Hold On; CWS On; SAS on	-	-	I	-	IV
III. Attitude Hold Off; CWS Off; SAS on	-	II	I	-	-
IV. Attitude Hold Off; CWS Off; SAS off	III	-	-	-	-

TABLE 14. MISSION TIME LINE VS FLIGHT CONTROL STATE



data base required for generating the top-level functional block diagram shown in Figure 12. This diagram illustrates the functional interface, the control flow, and the data flow for the COF system.

This data base is also required for starting the subsequently described implementation design of the data processing and non-data processing subsystems. These data are required for defining the man-machine interface control of these subsystems which, in turn, affects their structuring and functional partitioning.

Finally, this data base is required for initiating the system effectiveness evaluation process described in subsection 3.5. The operational state definitions and the time line relationships are the basis for developing the degraded state definitions and for enabling the entire quantitative state space-based estimations of the system's effectiveness for the mission.

3.3.2 Derivation of Control of Flight (COF) Functional Performance Requirements

After the top level COF functional performance requirements needed to meet the mission requirements have been used to derive the system functional architecture, the next task is to determine the performance requirements for the hardware and software to be used in these COF functions. These decomposed component requirements can take the form of measurement accuracies (for example, the accuracy with which target range is measured by a radar), operational characteristics (a radar altimeter measures the altitude accurately over the range of 100 ft to 40,000 ft), computational requirements, (a fire control algorithm may need an execution speed of

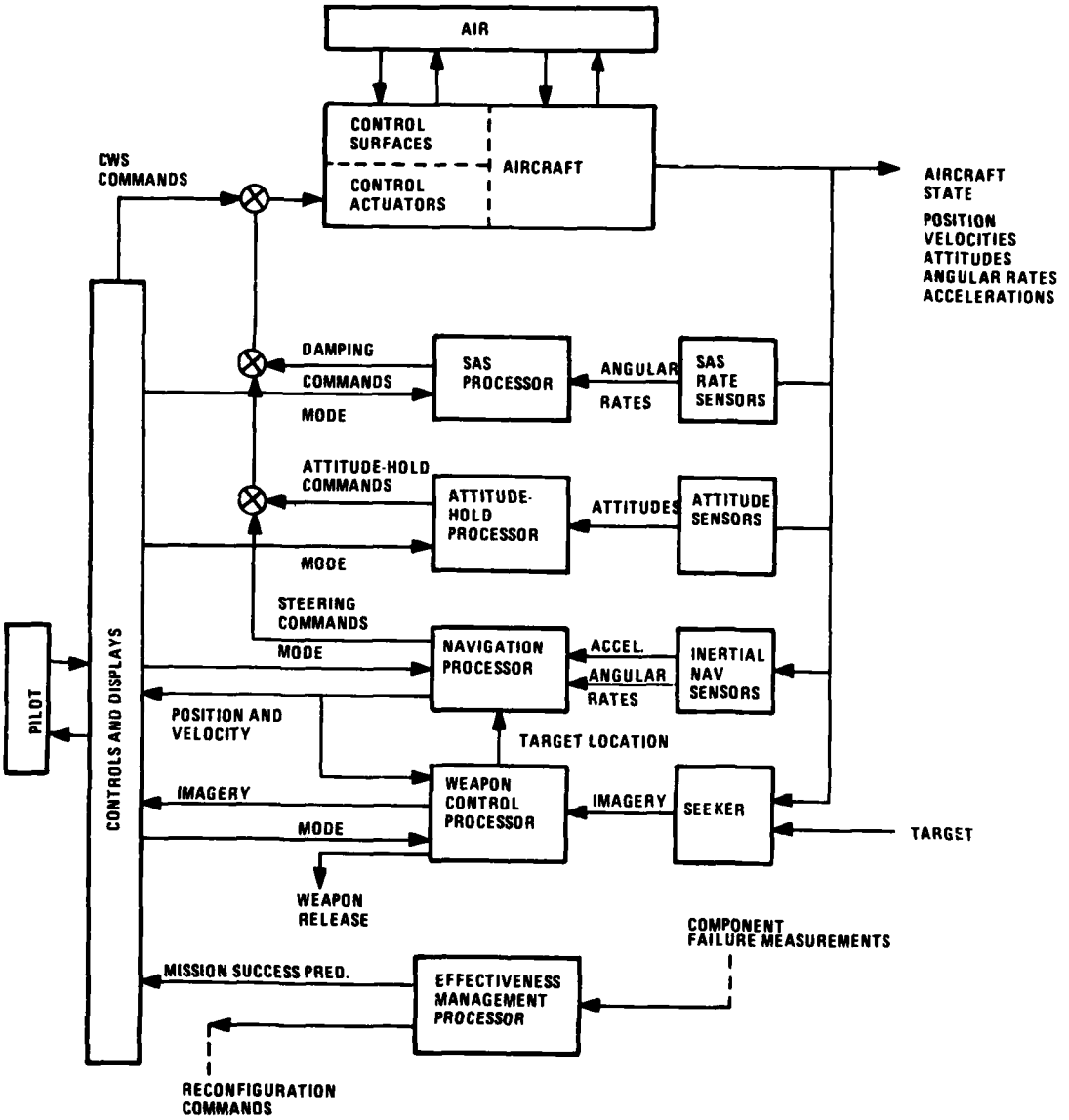


Figure 12. Top-Level Functional Block Diagram

1000 instructions per second), and so on. In general, the process of determining the functional performance requirements is an iterative one and consists of three major steps.

The first step is to select mathematical performance models for the various functional components to be used in COF of the mission. For example, the aircraft's performance can be described by means of 6 DOF equations of motion; whereas, the sensor models may consist of dynamics relating input/output of the sensor, with measurement accuracy treated as a parameter. This selection is a very crucial step. The complexity of these models will affect the amount of effort needed to evaluate the performance of the total system. Too simple a model for a hardware function can result in inaccurate performance requirements for both hardware and software functions. The second step is to select or design the various computational algorithms (software) needed for the COF functions. Typical examples are autopilot algorithms, fire control algorithms, etc. Here again the complexity of the computational algorithms will determine the amount of effort needed to evaluate the performance of the overall system. The third and final step is to select and apply the analytical techniques or tools which can use the mathematical performance models of hardware and the computational algorithms of the software functions to evaluate the system's functional performance and its integrated mission performance.

If the mission requirements are not satisfied, the designer selects or designs better computational algorithms for the software functions (this change may increase the amount of computation and hence the size of flight computer) or better performance for the hardware functions (this may increase the cost of hardware) to improve the overall system performance. Occassionally the designer may need to add additional hardware functions (such as more sensors) to meet the mission requirements.

In the following subsection, the various modern analytical techniques and tools that can be used to determine the functional performance requirements are given. This is followed by generic descriptions of the top-level COF functions.

3.3.2.1 Analytical Techniques and Tools for Computing Functional Performance--As noted previously, many phases and associated COF tasks are performed in any specific mission. In particular, for a weapon delivery mission some of the important COF tasks are given in the following list:

- Stability augmentation
- Navigation and position determination
- Energy management
- Terrain following, terrain avoidance
- Air-to-ground weapon delivery
- Sensor attitude control (Heading)
- Landing
- Effectiveness management

In order to evaluate the performance of the overall system with respect to the COF tasks and to determine whether or not it meets the mission requirements, various analytical techniques and tools must be made available to the designer. This subsection presents briefly the analytical techniques and tools selected for ICDT, the mission area of their application, and the amount of effort required to use them.

3.3.2.1.1 General Optimal Control Theory--This theory is applicable to dynamic systems represented by nonlinear differential equations and deals with the problem of selecting control inputs to minimize a performance index or a cost functional of control inputs and states of the system. Various numerical methods have been developed over the past 20 years to solve this class of problem. Prominent among them are the gradient methods and dynamic programming.[17]

In general, complex numerical techniques must be employed involving a large amount of data and numerous calculations. However, recent studies[18] have shown that when advanced numerical techniques are used in conjunction with the computational power of modern computers, reasonable solutions can be obtained for somewhat simplified nonlinear formulations of the mission phases.

The development of accurate fire control algorithms for air-to-air weapon delivery and nonlinear guidance laws for tactical missiles demands the use of general optimal control methods. However for the concept level design, linear optimal control methods discussed in the next section are considered to be sufficient.

3.3.2.1.2 Linear Quadratic Theory--The complexities and disadvantages of the general nonlinear theory have led to less general, but more tractable,

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[17] For a detailed discussion see S.J. Citron, Elements of Optimal Control, New York: Holt, Rinehard and Winston, 1969.

[18] P.M. Julich and A.J. McPhate, Optimal Guidance Using Microprocessors in a Real-Time On-Line Environment, AFATL-TR-77-127, November 1977.

formulations of the optimal control problem, known popularly as the linear quadratic theory.[19] Since most problems are nonlinear, several techniques have been developed and used to reduce them to a form that can be solved by linear quadratic theory. Some of these techniques are listed below:

- Eliminate the nonlinearities by approximating the nonlinear system by a linear model
- Linearize the nonlinear system equations about a nominal trajectory (obtained by using nonlinear equations) using small perturbation theory
- Linearize the nonlinear equations about the current value of the state and solve the linear quadratic problem on line at various points along the trajectory

Various software tools such as KONPACT[20] and ADAPS[21] have been developed to use linear quadratic theory. KONPACT represents an advanced computational tool for performing modern control synthesis, analysis, and design of automatic flight control systems. In addition, it interfaces with the aircraft mathematical models produced from such advanced programs as the FLEXSTAB.[22] The efficient and versatile Armament Delivery Analysis

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[19] B. D. O. Anderson and J. B. More, Linear Optimal Control, New York: Prentice-Hall, 1971.

[20] A. F. Konar and J. K. Mahesh, Active Control Synthesis for Flexible Vehicles, AFFDL-TR-75-146, Vol. I, II, III, June 1976.

[21] A. F. Konar, Development of Weapon Delivery Models and Analysis Programs, AFFDL-TR-71-123, April 1972.

[22] E. N. Tinoco and J. E. Mercer, FLEXSTAB, A Summary of the Functions and Capabilities of the NASA Flexible Airplane Analysis Computer System, NASA CR-2564, December 1975.

Programming System (ADAPS) was developed to implement the mathematical models for the analysis and design of weapon delivery systems. The aircraft model accommodates a wide variety of air frame nonlinear dynamics and measurement systems. The bomb model is general enough for a variety of dive bomb angles, release altitudes, and release speeds.

The main advantage of the linear quadratic theory is the multivariable aspect which makes it highly suitable for designing and analyzing integrated control systems. Any number of sensors can be considered and all available control mechanisms can be used, including unconventional ones such as direct side force.

In general, the process of applying linear quadratic theory to the design of integrated control systems involves the following steps:

- Determination of aircraft dynamics--Application of linear quadratic theory requires knowledge of the entire system state and of the dynamics of the system being controlled. The traditional approach consists of measuring dynamic pressure, altitude, airspeed, mach number, or some combination of them, and using stored information to estimate aircraft dynamics as a function of the measured parameters. The other approach, resulting in somewhat simpler dynamics, is based on using identification techniques[23] to

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[23] J. Howard, "The Determination of Lateral Stability and Control Derivations from Flight Data," Canadian Aeronautics and Space, Vol. 13, No. 3, 1967, pp 127-134.

determine the aircraft transfer function from the observed response of the aircraft itself. In most cases, however, the aircraft dynamics are an input given to the COF system designer by the aircraft manufacturer.

- Determination of sensor dynamics--Since all state variables of the combined aircraft and sensor system cannot be measured, it is necessary to estimate the values of the missing variables. This, in turn, requires knowledge not only of the aircraft dynamics but also of the sensor dynamics and noise characteristics. Simplified transfer function models with gaussian white noise provide enough accuracy for estimating the missing variables.

- Computation of Kalman filters--These filters are used to reconstruct or estimate the state variables of the system not measured directly by the sensors. Once the dynamics of the aircraft and the sensors are defined, the computation of the Kalman filter gains is straightforward and KONPACT software is ideally suited for this purpose.

- Selection of performance index or cost functional[24] to represent the COF performance--This is by no means straightforward and may require several iterations before a truly representative performance index is obtained. Recent research efforts at Honeywell[25] have produced some encouraging results towards making

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[24] Anderson and More, Reference 19

[25] G. L. Hartmann, C. A. Harvey, and C. E. Mueller, Optimal Linear Control Formulation to Meet Conventional Design Specs, ONR-CR-215-238-1, 1975.

the selection of the performance index straightforward by linking it to classical performance (for example, gain and phase margins).

- Computation of optimal control law--The computation of state feedback gains, to optimize the performance index, is done by using optimal control software (KONPACT). The control algorithm will consist of the Kalman filter dynamics and the state feedback gains.
- Determination of gain scheduling--This is necessary to accommodate various flight conditions of the aircraft. This involves repeating the computation of optimal control gains at various flight conditions.

Reference 26 contains a detailed application of the above process to designing a control system for the Drones for Aerodynamic and Structural testing (DAST) wing.

3.3.2.1.3 Navigation Error Analysis Techniques--Techniques are available for propogating the measurement errors within the navigation system and for analyzing the effect of each of these errors on the system's performance of the mission. In addition, Kalman filtering techniques and calibration and alignment techniques can be applied to reduce the effect of these measurement errors and improve the performance of the system.[27] NAVCOV[28] is a software tool that has been developed to conduct navigational

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[26] J.K. Mahesh, et al., Active Flutter Control for Flexible Vehicles, NASA-CR-159160, November 1979.

[27] For details see G.R. Macomber and M. Fernandez, Inertial Guidance Engineering, New York: Prentice-Hall, 1962.

[28] H.T. Gaines et al., Unaided Tactical Guidance, AFATL-TR-78-39, 1978.

error analysis and to design Kalman filters and develop calibration and alignment procedures to improve the performance of inertial navigation systems. This software tool can be used in repetitive fashion to determine the functional requirements of an intertial navigation system.

During the preliminary design of an inertial system, it is necessary to estimate its performance relative to the mission for which it is being designed. Since critical components used in the inertial system have errors associated with their performance, they will cause the system to have navigational errors. Gyro and accelerometer imperfections, for example, will propagate rate and acceleration measurement errors through the system, causing the computed values of vehicle velocity and position to be in error. By repetitive application of the NAVCOV analysis tool, the gyro and accelerometer error characteristics that can be tolerated for the mission can be determined.

3.3.2.1.4 Digital Control Analysis Techniques--These techniques can be applied to represent digital control systems and to analyze the performance of these systems as a function of computational parameters (that is, word length, sample rate, and computational delays).[29] Digital mechanization of COF functions on advanced aircraft concepts makes the application of these techniques a necessity. DIGIKON[30] is a software tool that has evolved

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[29] For details see A.F. Konar and J.K. Mahesh, Digital Flight Control Systems for Tactical Fighters, AFFDL-TR-73-119, June 1974.

[30] A.F. Konar and J.K. Mahesh, DIGITKON III User's Manual, F0636-TR3, March 1979.

at Honeywell to conduct digital control analysis efficiently. It can handle the multiloop, multirate control system implementations often required. This software tool is ideally suited for establishing the computational requirements of the flight control system. The details of using DIGIKON software to analyze and establish the computational requirements of the flight control system are given in Reference 29.

3.3.2.1.5 Nonlinear Analysis Techniques--Nonlinear analysis techniques available for computing weapon delivery performance and guidance system performance include traditional Monte Carlo techniques and direct statistical analysis methods. The Monte Carlo techniques essentially involve simulating the nonlinear system (for example, 6 DOF equations) repeatedly with different random parameters each time and then aggregating the results to get statistical performance measures such as Circular Error Probability (CEP) and Probability of Kill. The main disadvantages are the time required to do trade-off studies and the computer execution cost, since several hundred simulations have to be conducted to get a reasonable accuracy. CADET[31] and NCAP[32] represent software tools employing direct statistical analysis methods and represent state-of-the-art methods for analyzing the mission performance.

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[31] J.H. Taylor, Direct Statistical Analysis of Missile Guidance System Via CADET, Analytic Sciences Corporation, March 1976.

[32] A.F. Konar and J.K. Mahesh, Covariance Analysis of Nonlinear Systems, Honeywell IR&D Report, Applied Research, Vol. 2, March 1979.

The improvement in accuracy may not be significant enough to warrant the use of nonlinear techniques, rather than linear analysis, for concept definition studies.

3.3.2.2 The Flight Control Function--With respect to the overall mission, the flight control is an inner loop function. In many of the navigation and weapon delivery performance analyses for a mission, the flight control is implicitly assumed to be perfect. The advanced aircraft concepts, namely, Advanced Tactical Fighter (ATF), Control Configured Vehicle (CCV), and Advanced Fighter Technology Integration (AFTI), all reflect a continuing trend to aerodynamic configurations that obtain high maneuverability and reduced drag by compromising the static stability characteristics. This necessitates stability and control augmentation in all of the control axes for the safety of flight. Thus for the concept level design of ICDT, the flight control system may require consideration of those functions which are flight critical and those which directly improve the mission performance. Examples of these are described briefly below:

- Stability and control augmentation in all of the control axes for aircraft with marginal static stability
- Flutter suppression control to increase the flight regime of the aircraft
- Gust alleviation control to reduce the effect of wing loads and structural weights
- CCV control functions for obtaining lateral and vertical translations and directional control without sideslip or angle of attack (This improves the aircraft maneuverability and the weapon delivery accuracy.)

- Terrain avoidance control using a combination of radar altimeters and forward-looking radar data
- Threat avoidance control consisting of random flight path changes mechanized to be optimum for particular threats and flight conditions
- Automatic control functions (for example, heading control and auto landing) for most phases of the mission to reduce pilot work load
- Digital mechanization of flight control to provide enhanced reconfigurability and survivability

A block diagram of a generic flight control system that accommodates the flight critical functions is shown in Figure 13.

3.3.2.3 The Navigation Function--The advanced tactical fighter of the 1985 to 1990 frame will be equipped with some combination of inertial navigation, radio navigation, and alternative navigation systems.

Inertial navigation systems vary significantly in capability. At one end of the spectrum are the inexpensive, strapped-down systems with performance of 10 nmi/h. The electrostatically-supported gyro (ESG) navigators are at the other end with performance better than 0.1 nmi/h.

The global positioning system (GPS) provides a high rate, high accuracy update of position and velocity. The system is based on an array of satellites that continuously broadcasts range and position data to a passive receiver on the aircraft. This permits the computation of aircraft position and velocity with errors less than 10 feet and 1 ft/s respectively.

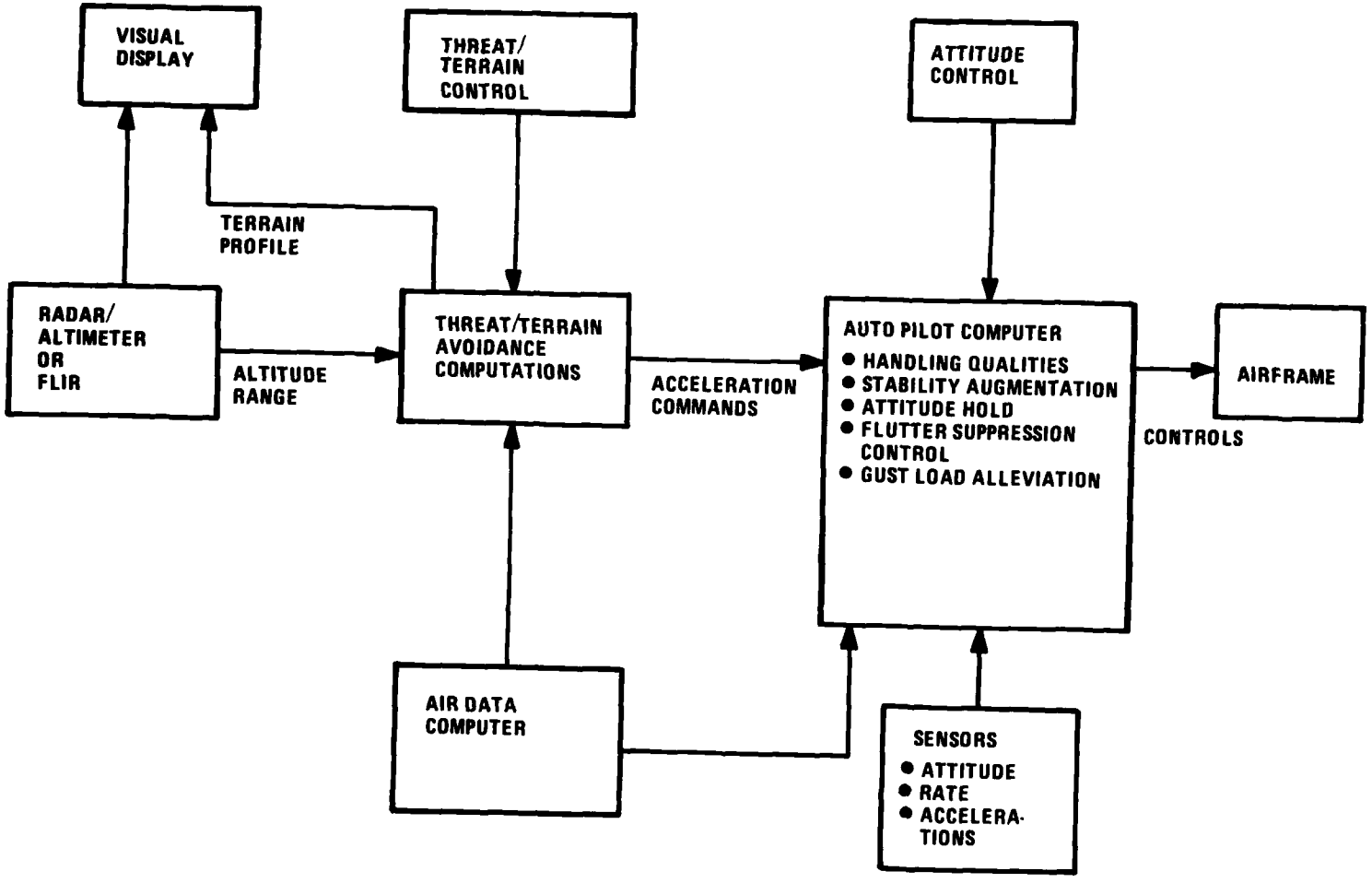


Figure 13. Block Diagram of a Typical Flight Control System

Terrain Contour Matching (TERCOM) and Microwave Radiometer (MICRAD) are alternative navigation systems that employ automatic checkpoint techniques. TERCOM senses the terrain profile with a radar altimeter and MICRAD senses the ground temperature profile with a radiometer. For each checkpoint map, the terrain profile or ground temperatures are prepared and stored in the navigation computer. When the aircraft approaches the checkpoint, the radar altimeter or radiometer senses the profile along the flight path and compares it with the stored data to identify the point of best match. This provides the position update to the navigation system.

A block diagram of the generic navigation system is shown in Figure 14.

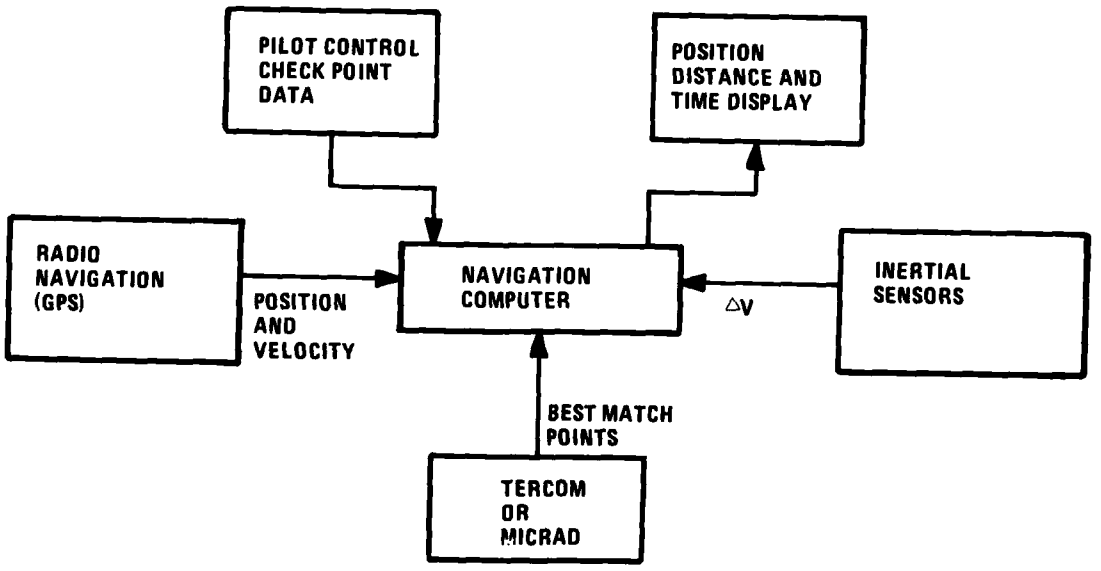


Figure 14. Block Diagram of the Navigation System

3.3.2.4 The Fire Control Function--Fire control is a computational function that uses the data from the navigation system, air data computer, target sensors, and weapon characteristics to aid the aircrew or pilot in launching the weapon under optimal conditions. To obtain very good weapon delivery accuracy, advanced bombing concepts are used for the unguided weapons.

3.3.2.4.1 Continuously Computed Impact Point (CCIP) Bombing Concept--This concept is incorporated in modern attack aircraft such as the A-7, F-111, and F-16. The system accuracy depends on the accuracy of the sensors measuring target range, wind, aircraft velocity, and attitude. Using the sensor data, the fire control computer continuously determines the current aircraft position and motion relative to the target and compares a computed impact point with the actual target position. The aircraft can be maneuvered in both pitch and heading (yaw) without disturbing the fire control solution. The heading must be corrected before the launch point is reached. Pitch maneuvers are continuously entered into the fire control computation so that weapon release occurs at any time the solution is correct. Figure 15 shows a block diagram of the CCIP fire control system.

3.3.2.4.2 Angle Rate Bombing System (ARBS) Concept--This concept depends on the target tracking sensor to provide accurate data on the line-of-sight angle and line-of-sight rate. This data plus altitude and air speed from the air data computer are enough for the fire control system to provide an accurate, automatic release of unguided weapons. This system has the advantage of not requiring accurate attitude information nor an accurate measurement of target range. With target tracking established, the fire

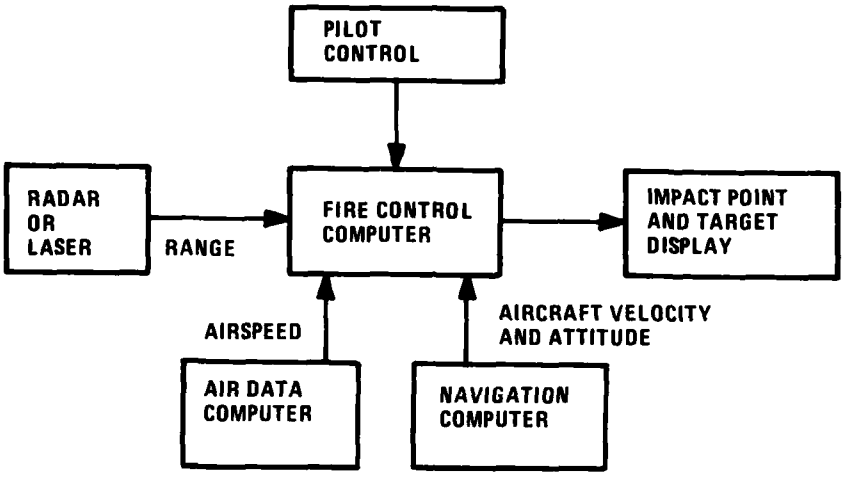


Figure 15. Block Diagram of the CCIP Fire Control System

control system provides target position and azimuthal steering information to the pilot via the visual display. Pitch maneuvers can be made during this time and are permitted during weapon release. Figure 16 shows a block diagram of the ARBS fire control system.

3.3.2.5 The On-line Effectiveness Management Function--The on-line effectiveness management function is primarily for monitoring the operability of the subsystems and for reconfiguring them as effectively as possible when a failure or damage is detected and identified. Along with these two sub-functions, the effectiveness management function predicts the probability of mission success based on the currently updated operability of the integrated subsystems. This prediction of mission success probability will be displayed to the pilot so that he can make management decisions to continue, abort, or modify (go after alternate targets) the mission.

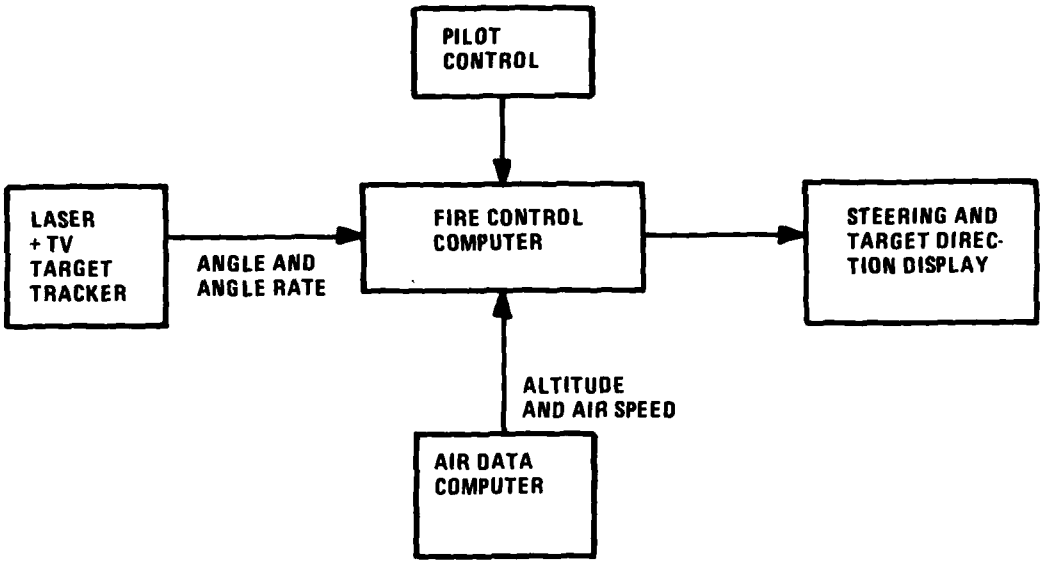


Figure 16. Block Diagram of the ARBS Fire Control System

The effectiveness management subsystem required for performing these functions will be a data processing subsystem implemented to perform:

- Subsystem failure appraisals based on built-in test equipment (BITE) measurements. These appraisals will be used to estimate the operability states (full, degraded, or failed) of the subsystems which are required for identifying the current probabilities of the system's availability (A), dependability (D), survivability (S), and capability (C).
- A determination of the designed-in reconfiguration capability that could be used to improve a failed or degraded state as it is detected and the generation of reconfiguration commands and the identification of a "reoperability" state achieved as a result of the reconfiguration action taken

- An instantaneous estimation of the current mission success probability based on the real-time computation of system effectiveness ($E = A \cdot D \cdot S \cdot C$)

A functional block diagram of an effectiveness management subsystem that will perform these functions is presented in Figure 17.

The failures monitored by the BITE measurements can be caused by inherent hardware and software problems or by effects of a hostile environment such as weapon firing.

The algorithms required for performing the functions indicated in the block diagram depend on the reliability, redundancy, and reconfigurability characteristics designed into the subsystems and the components and their interfacing units. The algorithm can be developed along with the reliability and reconfigurability design which is part of the subsystems interfacing design (substep 3I). A discussion of the sources of design data that will be required for developing the algorithms for each subfunction is given in the following subsections.

3.3.2.5.1 Algorithm Development for Failure Appraisal and Operational State Estimation--During the interfacing substep, 3I, of the implementation design, redundancy is designed into a candidate subsystem to meet the dependability goals. As part of this redundancy design, a failure analysis is made that relates specific component and subsystem failures to a set of operability states.

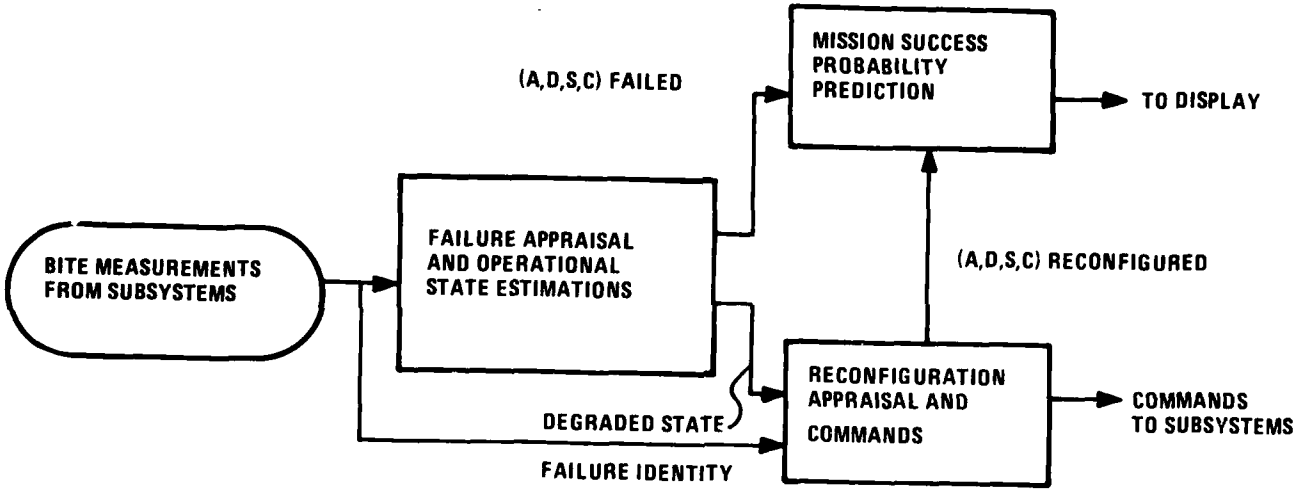
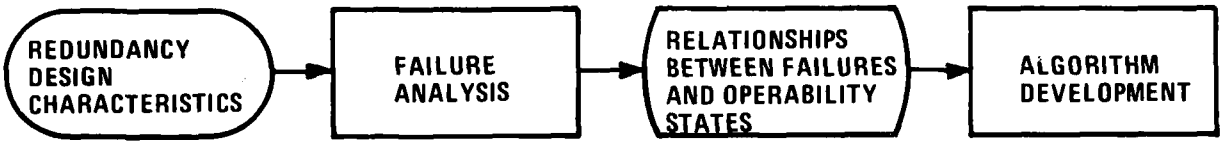


Figure 17. Effectiveness Management Functional Block Diagram

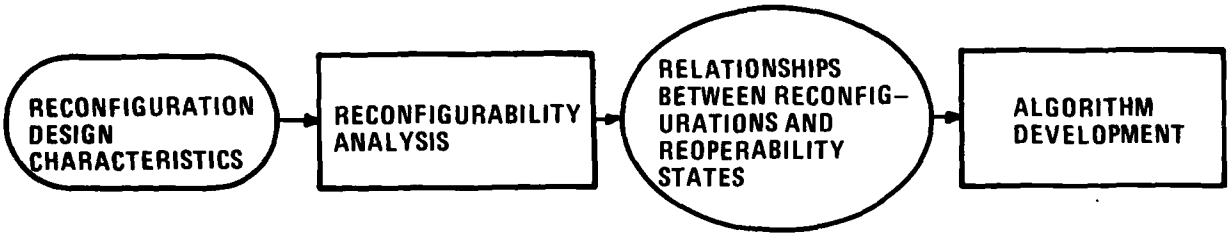
This set of operability states and the failures that cause transitions among them can be used to form the relationships that are the basis for the algorithmic design of the failure appraisal and operational state estimation subfunction. The flow of this process is illustrated as follows:



The algorithms take the form of a table look up that translates the identified failure to the system's operability state. Once the state is determined, it is transmitted to the system effectiveness calculation for an estimation of mission success probability.

3.3.2.5.2 Algorithm Development for Reconfiguration Appraisal and Commands--In addition to designing redundancy into the system candidate(s) during the interfacing design substep, 3I, reconfigurability is incorporated to provide survivability as well as additional reliability. The reconfigurability required is determined by the survivability analyses and design methodologies described in Section 3.4.4.3. The reconfigurability design determines the desirable and practical on-board switching of signals that can achieve useful transfers of subfunctions. This design process includes a survivability and reconfigurability analysis (similar to a failure analysis) that will relate the reconfiguration design possibilities selected to a set of upgraded operability states made possible by the on-board switching after a failure. These are identified as reoperability states; the relationships between

these states and the switching actions that cause them form the basis for the algorithm's design of the reconfiguration appraisal and command subfunction. The flow of the process for this subfunction is:



As in the case of the failure appraisal subfunction, the algorithm for the reconfiguration appraisal takes the form of a table look up. Once the reconfigurability state is selected, switching signals are sent to the components or subsystems and the reconfigured state identity is sent to the system's effective prediction subfunction for a subsequent estimation and updating of mission success probability.

3.3.2.5.3 Interactions with the System Interfacing Design Substep-- Because of the dependency of the algorithm development just discussed (3.3.2.5.1 and 2) on the characteristics of the implemented redundancy and reconfigurability designs, it becomes necessary to interlace the functional design of the effectiveness management subsystem with the system interfacing implementation design described in subsection 3.4.4. This interfacing is done by following the substeps illustrated in Figure 18.

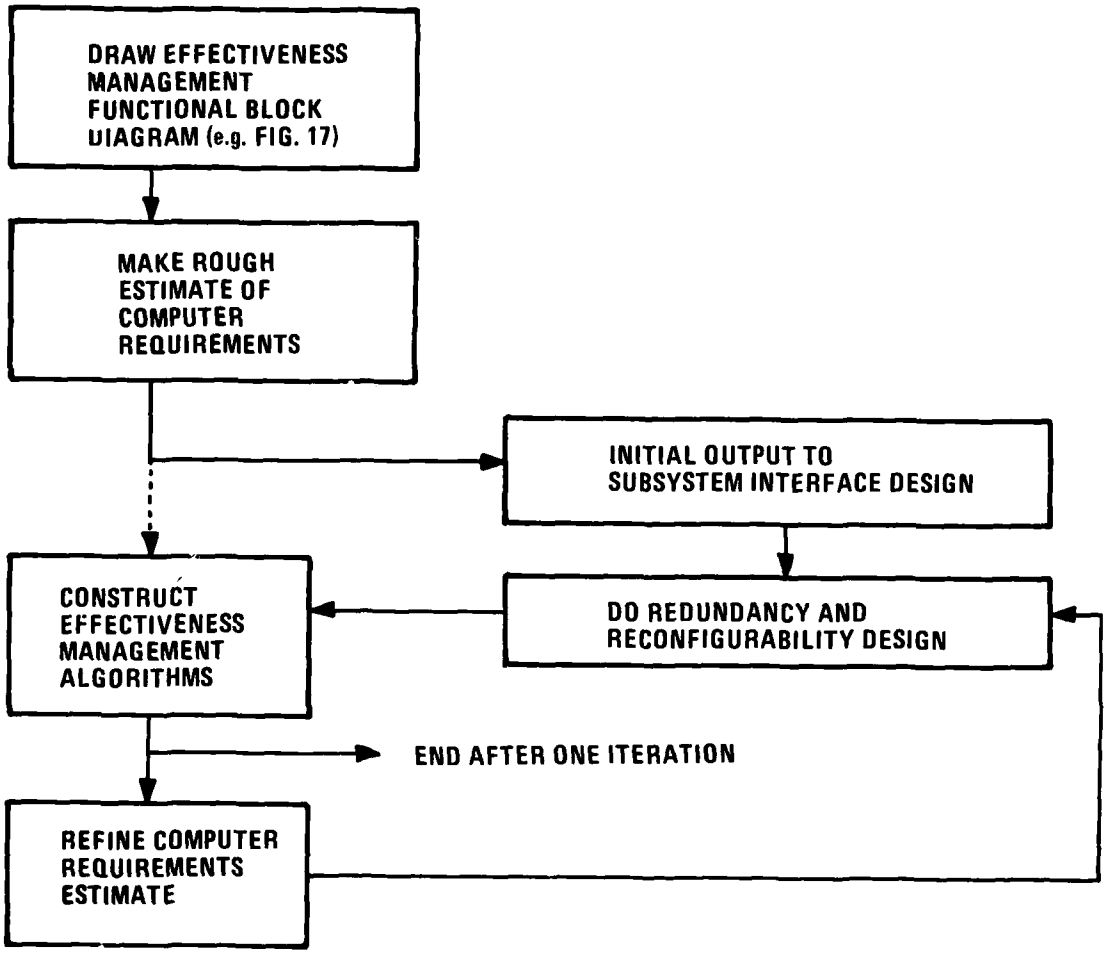


Figure 18. Interlacing of the Effectiveness Management Functional Design

3.3.2.5.4 Algorithm Development for On-Line Mission Success Prediction--As stated earlier, the probability of mission success is based on the real-time calculation of system effectiveness, E = ADSC. The formulas and mathematical process for making this calculation during the system design process are discussed in detail in Section 3.5. To make an on-board real-time estimation of E, the four matrixes or vectors

representing A, D, S, and C at the beginning of the mission are stored in an on-board computer. The elements of these matrixes or vectors are the probabilities of changing from one state to another. When a failure and/or a reconfiguration causes a change in state, the affected elements of the initial matrixes must be changed to zeros or ones and a calculation of the current system effectiveness can be performed by a multiplication of the matrixes.

The accuracy of the mission success prediction depends on the validity of the elements of the A, D, S, and C matrixes which, in turn, depends on:

- The accuracy of modeling the design characteristics of the system
- The accuracy of modeling the threat characteristics
- The concurrency of the elements with respect to the system configuration, the threat environment, and the mission plan.

Consequently, a simulator to perform a recalculation of the elements of the matrixes before each mission may be required as ground support equipment in order to make the effectiveness management system an accurate predictor, in addition to being a reconfiguration management tool.

3.4 DESIGN OF CANDIDATE SYSTEMS

The outputs of the functional requirements derivation are oriented along the operational function lines defined in step 1. They must be reoriented to the basic data processing and non-data processing functional alignments by judgmental allocation before the implementation design can begin.

3.4.1 Allocation and Integration of Functional Requirements to the Basic Subsystems

The allocation and integration process is diagrammed for illustrative purposes in Figure 19.

First the requirements for each operational function are divided into the sensing, processing, or actuation categories that can best handle the process involved and achieve the performance desired. Then any integrations of these functions that will eliminate redundancies are made. Next the resulting sets of sensing and actuating functions are allocated to the basic non-data processing design category and the processing to the basic data processing design category. The design processes for these two basic subsystem categories are distinctly different and the allocation of functions must occur before the implementation design can be started. This initial substep of the candidate system design process, the functional architecture of the candidate system, provides the basis for driving to the system implementation architecture as indicated in Figure 20.

The design of the non-data processing subsystem for a COF system is essentially a selection of the best combinations of sensors and actuators to meet the functional and performance requirements. A process for the selection of optimal combinations of sensors was previously developed

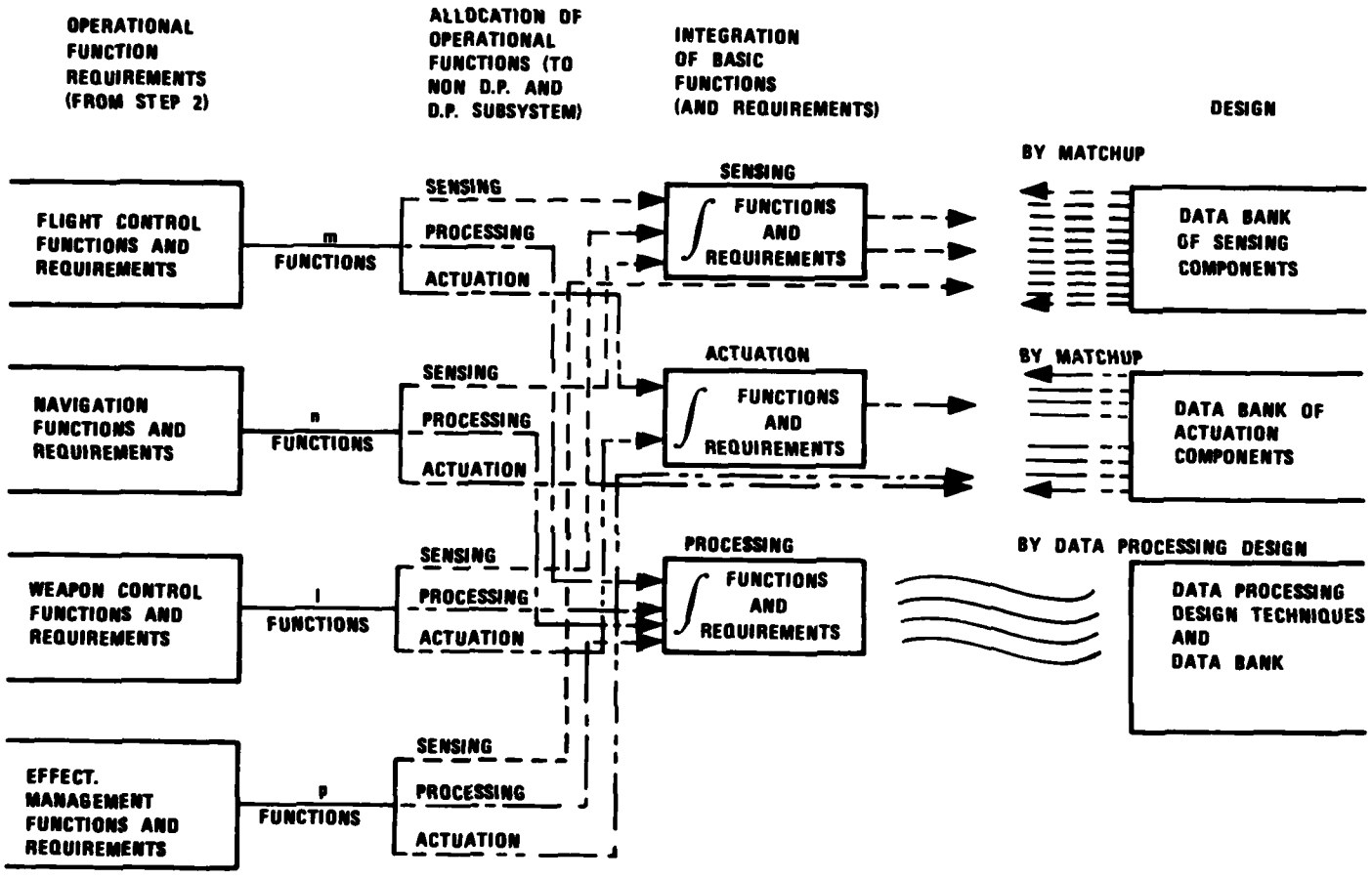


Figure 19. Allocation and Integration of Functions

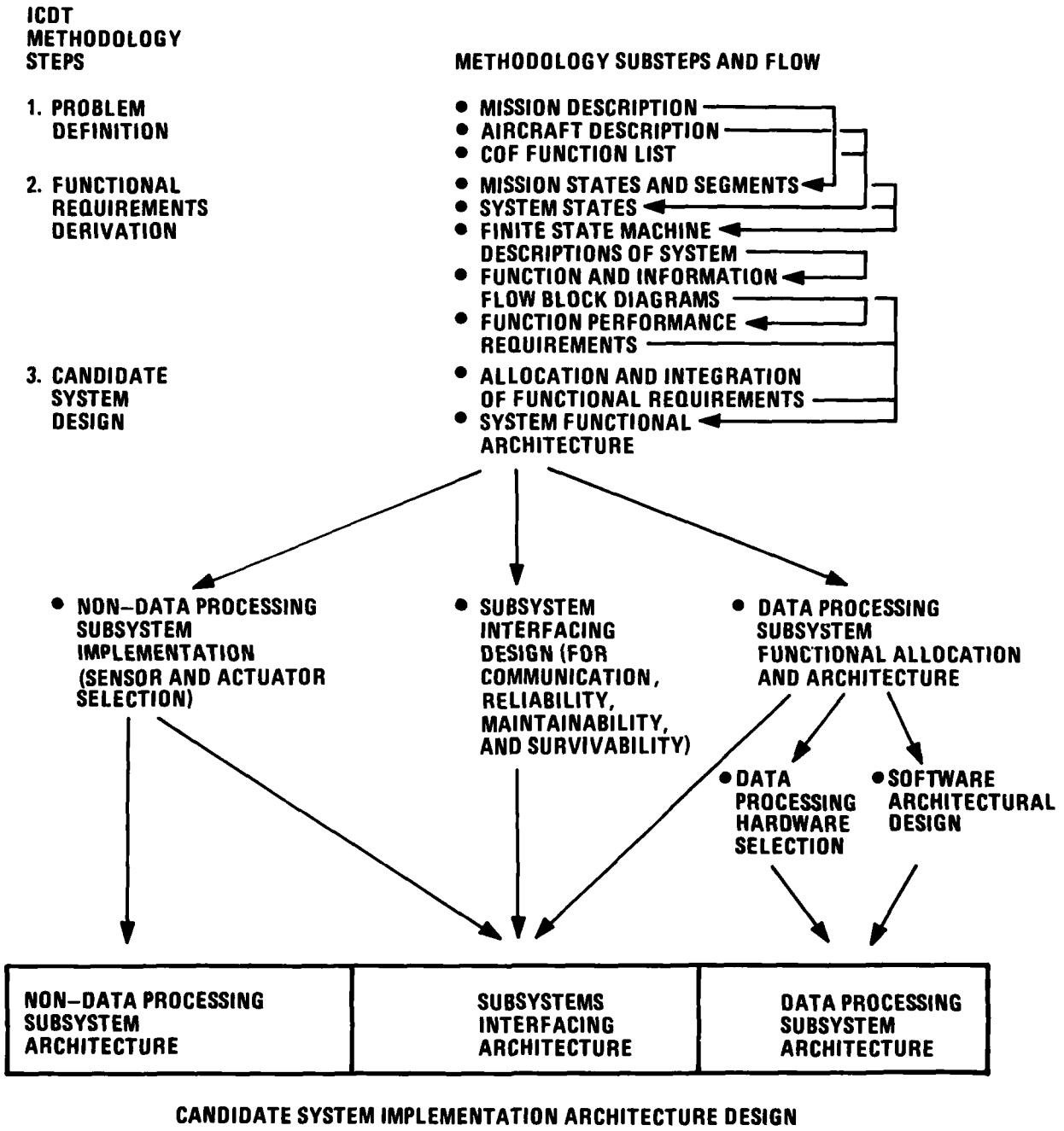


Figure 20. How ICDT Methodology Flow Drives the System Architecture Design (at Concept Definition Level of Detail)

and has been adapted to the selection of both the sensors and the actuators for application in the ICD methodology. The characteristics of various candidate sensors or actuators are pre-stored in a data bank and then matched against the functional and performance requirements and against cost and effectiveness requirements in so far as these requirements are specified at the component level. The match-up is performed in a manner that permits an integration of functions at the component implementation level by considering multi-function as well as single-function sensors and actuators and storing their characteristics in the data bank. A more detailed description of the match-up methodology for the non-data processing subsystem design is given in Section 3.4.2. This technique is implemented in the demonstration example given in Section 4.0.

The design of the data processing subsystem, as illustrated previously in Figure 8, is divided into two separate branches. These branches are the design of the software and the design of the data processing hardware. The design of the software is a unique process, but the design of the data processing hardware is similar to and handled along the lines of the match-up design procedures for non-data processing subsystems. Prior to the branching, the data processing requirements must undergo a context translation from being expressed in operational-oriented parameters and descriptors to being expressed in data processing-oriented parameters and descriptors. This translation and the separation of the software and hardware functional requirements are handled by a design approach utilizing both finite state machine (FSM) generation and hierarchical structuring. The methodology is more fully described in Section 3.4.3.

3.4.2 Design of the Non-Data Processing Subsystem

As a starting point, we have functional performance requirements derived from the mission requirement of finding a target and destroying it with a certain probability of success. The end point is a selected set of actuators and sensors which, when interfaced with the data processing subsystem, will permit the aircraft to meet these requirements. The design resources we are starting with are a known set of available sensor and actuator hardwares and their known or projected cost, reliability, and capability.

To synthesize the sensor/actuator subsystem, the mission performance requirements, decomposed into functional performance requirements at the same level at which hardware capabilities are characterized, are met by finding the set of components with the highest value of the figure of merit being applied (maximum performance, lowest cost, etc.).

To illustrate the design process more clearly, the requirements decomposition technique will be reviewed. The starting point is a specification of all missions for which the aircraft is intended to be used (for example, bombing, air-to-ground strafing, air-to-ground missile delivery, etc.). Each of these individual missions is then described in terms of functional segments (take-off, flight to target area, target acquisition, approach, ordnance release, damage assessment, return) and mission performance requirements (97 percent probability of target destruction (PD), 99.9 percent probability of intact return). Achievement of the overall mission requirements will depend on the ordnance effectiveness, assumed to be a known quantity, plus achievement of certain performance levels for at least some of the mission segments. Examples could be location and recognition of the target,

approach to release point on a minimum risk trajectory, and release of weapons at the correct relative location with respect to the target (R). In each mission, therefore, a set of functional requirements relating both to sensor and control issues can be derived. This process is then repeated for all specified missions, and the resulting sets of functional requirements are combined. There will certainly be overlap and repetition between various sets; in some cases the requirements for a mission in one area may be more stringent than those in another, and only the more stringent requirements will be retained. Thus the overall set of aircraft functional requirements will be somewhat smaller than the sum of the sets of mission functional requirements.

The next step is to decompose the set of aircraft plus COF system functional requirements into a set of specific sensor requirements and a set of actuator requirements. Examples of the former would be: acquisition of a target at 5 km with PD of 95 percent, angular tracking of target during approach to $\pm$5 deg and measurement of range to target of $\pm$20 feet. Examples of the latter would be maintenance of aircraft attitude during approach to $\pm$X, maintenance of air apeed between 235 and 250 mph, and performance of a particular maneuver within a specified envelope. When this step has been accomplished, the derived sets of sensor and actuator requirements have been entirely decoupled from specific missions or mission segments. The complete set of requirements is now responsive to the overall aircraft mission, and there is no longer a direct assignment of individual actuators and sensors to specific mission functions.

At this point we have a specific set of functions to be accomplished by the actuator and sensor set to be selected. For every single function, a particular piece or class of hardware is relevant. As an example, consider target acquisition. This could be accomplished by the pilot's visual mechanism, by a radar set, or by a forward-looking infrared device (FLIR). The latter two sensor classes will each contain a number of specific types. Each type will have specific capabilities relating to probability of detection of different types of objects as a function of range, background, weather conditions, etc. Each type will have a known (or projected) cost, reliability, repairability, and survivability. Now consider a set of missions requiring both air-to-ground and air-to-air capability. Target acquisition performance requirements will now be specified for two different situations, a 5 m^2 radar target at 30 miles (aircraft) and a 10 m^2 target at two miles against ground clutter (tanks). These two functional requirements are satisfied by finding a sensor or sensors with capabilities which meet or exceed those required. If a single sensor will serve both purposes, it would be advantageous to select it, unless two less expensive units would have lower cost, and/or if redundancy requirements dictate multiple units. Clearly the issues of reliability, availability, survivability, and redundancy complicate the issue beyond a simple matching of capabilities and requirements. These issues, however, can be dealt with as described in the section on subsystems interfacing design (Section 3.4.4).

In principle, requirements decomposition is straightforward and, when accomplished, permits an equally straightforward system selection and specification. In practice, it is one of the most difficult steps in the methodology. All tools which have ever been developed for the design and evaluation of sensor and actuator subsystem effectiveness work in the other direction, that is, bottom-up. The components are specified and the performance resulting from their employment determined. Nothing has been available which would start from a specified system performance level and determine the required component capabilities.

Given the decomposed sensor and actuator requirements, all that is really required for a design process is to establish a means by which a designer can match up performance requirements with sensor/actuator capabilities. A simple and direct way that this could be done would be to exercise existing methodologies for the evaluation of the performance of components for a large number of component sets and then tabulate the results. This component performance tabulation could serve as a look-up table for the computer, and an association could immediately be made between component performance requirements and capabilities.

The accuracy of this approach in terms of meeting mission requirements will depend on the fineness of the grid (how many component data points are in the tabulation). The ultimate accuracy will be achieved when the component number is infinite, which becomes the case for resident inverse algorithms.

The prologue to the design methodology then involves the decomposition of missions to mission segments and functions and the decomposition of mission requirements to component requirements. The association of sensor and actuator performance characteristics with each functional requirement can then be accomplished. The latter step will be implemented by establishment of performance and requirement tabulations, and computer look up between them.

3.4.2.1 The Impact of Integrated Control Systems--What emerges from the above process is an assortment of black boxes which can be interfaced as efficiently as possible and tested. This study, however, is directed at the integration of control functions. In order to design a truly integrated sensor/actuator system, another level of sophistication is required. Until now in this description, each sensor/actuator has been considered to perform complete functions. An inertial navigation sensor would output location coordinates; a radar would output the range, angular coordinates, and cross section of an object at which it was pointed. An altimeter would provide a reading of the altitude of the aircraft. Integration of functions at this level would involve either redundancy (for example, altitude determinations with a radar set) or the sharing of processing capability. The ultimate aim of integration would be, however, to utilize all of the sensing and activating capabilities of all on-board hardware, in order to optimize system survivability and reliability and minimize cost and weight. As an example, consider the situation in which the fire control radar loses its range gate but retains the ability to measure the angular location of the target. From a functional standpoint, the sensor can no longer provide complete target location information. In a truly integrated system, however, the target angular coordinates plus altitude data from the altimeter

and aircraft orientation data from the attitude reference, if available at a central processing location, could be used to reconstruct the required data to a high degree of accuracy.

It is not conceptually easy to do component and function integration at this level. Different sensors and actuators operate on different physical principles and are designed for apparently divergent functions. To deal with them on a common basis, they must be described in the same set of terms. The key issue thus becomes the description of both the performance requirements and available hardware characteristics in the same language. In principle, there would be multiple aircraft and target parameter sets which could serve this purpose. In practice, the most direct and least confusing solution set usually proves to be the lowest level set applicable to locate the aircraft position in an earth-centered coordinate system and to describe its orientation with respect to these coordinates. Also needed would be the coordinates of any target relative to the aircraft and to the local airflow direction. In principle, if all coordinate parameters are known, their first derivatives can be approximated by comparing successive measurements. In some cases (velocity, for example) the first derivative plays such an important role in aircraft function that it must be determined to a higher degree of accuracy and a direct measurement is required.

These mission parameters, it should be noted, are common to both sensors and actuators. Sensors determine the parameter values to some degree of accuracy, and actuators alter them. Sensors also have associated with them a small set of unique parameters which describe their ability to locate a target (such as field of view). Table 15 presents a first-cut listing of the parameters required to characterize the performance of sensors and

TABLE 15. IRREDUCIBLE PARAMETERS

	Parameter	First Derivative	Actuator
Aircraft location relative to earth-centered coordinates	Latitude	X	X
	Longitude	X	X
	Altitude (absolute)		
	Altitude (relative to local topography	X	X
Aircraft attitude (relative to earth-centered reference)	Pitch	X	X
	Roll	X	X
	Yaw	X	X
Aircraft attitude (relative to local air flow)	Sideslip		X
	Angle of Attack		X
Location of any other object (target) relative to air craft	Azimuth	X	X
	Elevation	X	X
	Range	X	X
	Sensor FOV		
	Data Rate		
	Normalized Spatial Resolution		
	Normalized Detection Range		

actuators of an avionics system at the level required for total system integration. All parameters listed apply to sensors. Those for which a direct determination of first derivative may also be required are indicated by the presence of an x in the column labeled First Derivative. Those which are also applicable to actuators are indicated by an x in the Actuator column. The key feature of the parameters in this set is that they are irreducible, that is, none can be determined by measurement of any combination of others.

3.4.2.2 Sensor Integration Methodology

In order to simplify the description of the way in which this parameter set would be used to design an integrated avionics system, let us consider a case in which survivability and reliability are not issues, and consider availability to include adverse weather situations. Three steps are then required to achieve the objective. The first step is to express mission requirements in terms of an irreducible parameter set. This step would begin with the process, described earlier, of functional decomposition. It goes beyond this point, however, in that the mission requirements are reduced, not only to sensor and actuator functional performance requirements, but to performance requirements expressed in terms of measurement or control of the irreducible parameters. In some cases, such as that of an altimeter, these levels are indistinguishable. In others, such as a FLIR, or a pilot, the level may involve quite different parameters.

Step two is to catalog the performance capabilities and costs of the candidate hardware items in this same terminology. When this has been accomplished, step three, the design of an integrated system, can proceed in a methodical manner. This basically entails selecting components which fill one or more performance requirements in order of increasing cost until all requirements are met. In this simplified scenario, each mission set would result in the specification of particular values to be achieved for the measurement and control of each irreducible parameter. Each candidate hardware item would be characterized by its ability to measure or control each parameter and by its cost.

An example of this catalog and of the data to be included for the APN-222 altimeter is shown in Table 16. In Section a of Table 16 the previously defined irreducible parameter set is shown for this sensor. In this case the only parameter measured is relative altitude. The accuracy obtained and the range of operation are shown. Sections b and c of Table 16 indicate the environmental restrictions placed on sensor operation (these are in the areas of pitch and roll and temperature range) and the cost data. These latter include volume, weight, and power requirements, as well as reliability data (mean time between failures would be the desirable format for this parameter).

Preparation of the data for the demonstration example has been somewhat difficult, because no general tabulation of the required data for all available avionics equipment appears to be available. Fairly complete tabulations of APN numbers and descriptions are available, but the descriptions lack the required detail. It will probably be necessary, therefore, to develop this data piecewise from a variety of sources in the next phase of this design methodology development.

TABLE 16. CATALOG OF PERFORMANCE CAPABILITIES AND COSTS

Device Designation

APN-222 Altimeter

a. Capabilities

	Parameter	Value ±	Rate ±	Accel ±
Aircraft location relative to earth-centered coordinates	Latitude Longitude Altitude (wrt earth center)			
	Altitude (local relative)	5 ft + 0.5 percent alt		
	Operating range	max 70,000 ft min 0 ft		
	Activity warning (high/low)			
Aircraft attitude (relative to earth-centered reference)	Pitch Roll Yaw			
Aircraft attitude (relative to local air flow)	Sideslip Angle of attack			
Location of other objects (targets) relative to air craft	Azimuth Elevation Range Sensor FOV			
Other sensor parameters	Data rate Normalized detection range Normalized spatial resolution			

b. Restrictions

Track rate	10° at 70,000 ft
Pitch and roll	20° at 35,000 ft
Temperature	
On (F)	-55 - +71
Off	-65 - +95
Weather	

c. Cost

Vol (in^3)	168 56 18
Wt. (lbs)	6.5 2.5 1.0
Power (watts)	35 @ 28 DC 15 @ 28
Life (hours)	10,000
Operational Stability (hours)	1,000

3.4.2.3 Outline of Overall Process

A view of the overall ICDT design methodology highlighting the sensor subsystem selection step is presented in Figure 21. It should be noted that the performance requirements derived by Steps 1 and 2 may be a number of sets of values for the basic sensor (or actuator) parameters, rather than just one. This plurality of sets is due to several factors: for example, trade-offs between performance for various parameters are possible, which do not affect the functional outcome. For some sensors, for example, acquisition range, data rate, angular resolution, and range resolution, can be traded in various ways. Also, requirements for performance for different parameters may not be independent. It would be possible in some cases, for example, to relax angular rate accuracy if range were known.

There will, generally, be more than one set of the candidate sensor sets which will meet the sensor performance requirements. The sensor selection methodology recommended for substep 3G uses life-cycle cost as the variable parameter and evaluates the selected sets in order of increasing cost.

3.4.3 Design of Data Processing Subsystem

At this point in the design process, the mission and system requirements have been analyzed and decomposed into system functions, subfunctions, and modes. The functional requirements for the non-data processing elements of the system, particularly the sensors and actuators, have been identified. The functional requirements for data processing elements

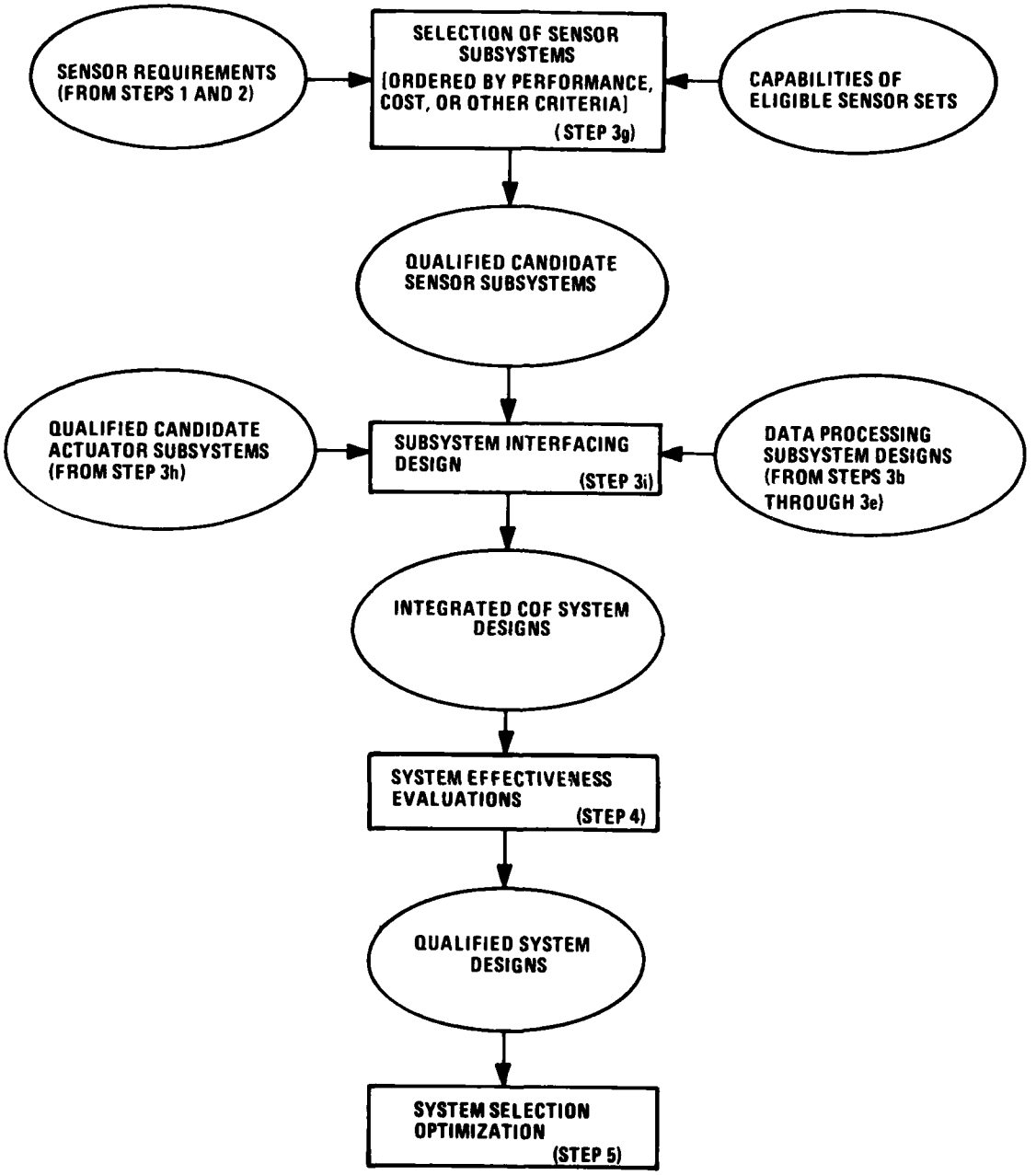


Figure 21. ICDT System Design as Driven by Subsystem Designs

of the flight control, navigation, weapon delivery, and effectiveness management operational functions have been determined. Modes, displays, sensor inputs, block diagrams for implementating the control laws, and other calculations have been specified. The values of the parameters used in the computations of leads, lags, and filters have been estimated. The task now is to translate this information into a format and terminology that will permit appropriate analysis of the data processing requirements and that will facilitate the hardware and software implementation of these requirements.

Eventually, the design of the data processing subsystem will be aided by interactive access to a large data base. A great amount of experience and data has been accumulated on the computational requirements for control of flight systems. This material can be catalogued in a design data base and called upon interactively to provide estimates of required throughput, memory, and so on. These requirements can then be matched to available computer configurations. These computer design aids will not be developed in the following design discussion, but it should be clear how much of the design process may be automated.

3.4.3.1 Translation of Allocated Functional Requirements into Data Processing Subsystem Performance Requirements--The ICD methodology for concept definition goes as far as a preliminary design of the software but stops before detailed design and coding begin. However, an accurate and complete description of the requirements will ultimately be needed to detail design, code, and verify the software. Thus, the ICD methodology must produce preliminary designs that are described in a manner that allows convenient extension to detail when the design process is continued.

The design process begins by reformulating the requirements for data processing into a more appropriate format.

The following list is compiled:

- Each operational function, its inputs and outputs
- Assumptions made for each function
- Performance requirements that may be the most difficult to achieve
- Each interface between the data processing functions and the rest of the system
- Any special non-digital data processing (for example, analog backup systems)
- Any other assumptions made to complete the description of the requirements

The next task is to translate these operational function requirements into computational requirements. The process will be explained by following the particular example of the flight control subsystem design. The computing aspects of each block in the COF system block diagrams and the rates of computation have been determined in the previous step. A typical list of computational items for the flight control function is shown in Table 17. The sample rate is generally taken to be at least five times greater than the highest frequency of interest. Representative sample rates for autopilot functions are given in Table 18. In safety critical systems, the required reliability is obtained by using redundant channels.

TABLE 17. DIGITAL SIZING ESTIMATES--HDP-5301 COMPUTER

Function	Memory Requirements			Computation Time
	Instr	Const	Spad	
Lag	13	1	2	30
Hipass	13	1	2	30
Symmetrical limiter	12	1	-	18
Deadband	7	1	-	9
Integrator/Limiter	21	2	2	43
Notch filter	23	4	4	66
Lead/Lag	13	3	2	41
Hysteresis switch	29	3	1	25
Synchronizer	6	-	1	11
Gain schedules				
1 Slope and 2 BPs	17	6	1	33
2 Slopes and 3 BPs	26	9	1	40
3 Slopes and 4 BPs	35	12	1	47
2 Slopes and 1 BP	20	5	1	31
Fader	13	1	1	28
Gain	1	1		8
Univariate function	50	50		185
Bivariate function	125	150		455

TABLE 18. SOFTWARE COMPUTATIONS VERSUS SAMPLE RATE

Software Elements	Sample Rate (Hz)			
	40	20	10	5
Executive	X			
Pitch SAS	X			
Lateral SAS	X			
Pitch A/P		X		
Roll A/P		X		
APW*		X		
ADC†		X		
BIT‡		X		
Inlet system	X			
Mode logic			X	
Discrete inputs				X

*Automatic pitch warning
†Air data computation
‡Built-in test

An example of these redundancy requirements is shown in Table 19. The memory and processor sizing requirements can be estimated from the block diagrams, from the derived data illustrated, and from previous experience with similar systems. The flight control example is carried through in Table 20 and summarized in Table 21. The four columns of computation times listed in Table 20 represent a preliminary allocation to subframes in the usual rate structure executive program which accommodates the different sample rates.

In this manner a preliminary outline of the required calculations and estimates of the computational load can be obtained for each operational subsystem. The estimates rely to some extent on previous experience and knowledge of how these avionic computations have been handled.

TABLE 19. REDUNDANCY MANAGEMENT REQUIREMENTS

System	Sensors	Electronics	Servos
Pitch SAS	Fail Op, Fail Safe	Fail Op^2, Fail Safe	Fail Op, Fail Safe
Yaw SAS	Fail Op, Fail Safe	Fail Op^2, Fail Safe	Fail Op, Fail Safe
Roll SAS	Fail Safe--Manual select functional sensor after first failure	Fail Op, Fail Safe	Fail Safe--Manual select for reduced performance after first failure
Pitch A/P	INS Fail--Select FRS	Fail Op, Fail Safe	Same as Pitch SAS
Roll A/P	INS Fail--Select FRS	Fail Op, Fail Safe	Same as Roll SAS
ADC	Fail Op, Fail Safe	Fail Op, Fail Safe	Not applicable
APW	Fail Safe	Fail Op, Fail Safe	First fail Inop
Inlet	First fail--Manual select failed side	Fail Op, Fail Safe--Manual select failed side	First fail Inop

Note:
- Fail Op^2, Fail Safe (System operational after two failures and fails safe for third failure).
- Fail Op, Fail Safe (System operational after one failure and fails safe for second failure).
- Fail Safe (System fails safe for first failure).

TABLE 20. SOFTWARE SIZING ESTIMATES

Function	Memory Requirements			Computation Time - Milliseconds			
	Instr	Const	Spad	S.I. #1	S.I. #2	S.I. #3	S.I. #4
Air Data Computer	612	97	51		2.0		2.0
Mode Logic	500	10	20	0.436			
Pitch Sas							
1 - Lag	13	1	2	0.030			
2 - Lead-Lags	26	6	4	0.082			
4 - Limiters	48	4		0.092			
1 - Q_c Schedule	17	6	1	0.033			
4 - Gains	4	4		0.032			
1 - Switch	3			0.009			
SUBTOTAL	111	21	7	0.258	0.258	0.258	0.258
Lateral SAS							
1 - Hipass	13	1	2	0.030			
2 - Q_c Schedules	34	12	2	0.066			
1 - Switch	3			0.009			
8 - Gains	8	8		0.064			
3 - Limiters	36	3		0.054			
1 - Notch	23	4	4	0.066			
SUBTOTAL	117	28	8	0.289	0.289	0.289	0.289
Pitch Autopilot							
2 - Lags	26	2	4	0.060			
2 - Hipass	26	2	4	0.060			
1 - Notch	23	4	4	0.066			
1 - Integrator	21	2	2	0.043			
1 - Variable Lag	54	13	4	0.110			
5 - Limiters	60	5	-	0.090			
2 - Synchronizers	12	-	2	0.022			
1 - Fader	13	1	1	0.028			
2 - Hysteresis Switch	58	6	2	0.050			
3 - P_s Schedules	36	18	3	0.098			
3 - Gain Schedules	105	36	3	0.141			
1 - 2 Var. Schedule	63	22	2	0.097			
29 - Gains	29	29	-	0.232			
12 - Switches	36	-	-	0.108			
SUBTOTAL	562	140	31	1.205	1.205		
Roll Autopilot							
1 - Integrator	21	2	2	0.043			
2 - Synchronizers	12	-	2	0.022			
2 - Limiters	24	2	-	0.036			
1 - Mach Schedule	17	6	1	0.033			
8 - Gains	8	8	-	0.064			
1 - Switch	3	-	-	0.009			
SUBTOTAL	87	18	5	0.207	0.207		

TABLE 20. SOFTWARE SIZING ESTIMATES (CONCLUDED)

Function	Memory Requirements			Computation Time - Milliseconds			
	Instr	Const	Spad	S.I. #1	S.I. #2	S.I. #3	S.I. #4
Inlet Control System							
P_tP_s and Mo Computations	400	60	30	1.09	0.365		
18 Analog Inputs	54		18	0.09			
6 Analog Inputs	18		6	0.03			
2 Discrete Inputs	4			0.01			
4 Discrete Outputs	8			0.015			
6 Bivariate Functions	750	900		0.91	1.81	Same as	Same as
2 Univariate Functions	100	100		0.36	0.18	S.I. #1	S.I. #2
1 Absolute Value with Threshold	6	1			0.02		
2 Limiters	24	1		0.02	0.02		
3 One sided dead bands	21	1		0.06	0.06		
5 Three Input Sums	3			0.026	0.026		
1 Lead Lag	13	6	2	0.041	0.041		
10 Gains	10	10		0.054	0.054		
1 Unstart Logic	100			0.094			
SUBTOTAL	1515	1079	56	2.80	2.576	2.80	2.576
Subtotals if Both Inlet Computations are Done in Each Computer	3030	1079	112	4.51	4.787	4.51	4.788
APW							
1 - Lead Lag	13	3	2		0.041		
1 - Limiter	12	1			0.018		
1 - Switch	3				0.009		
2 - Mach Schedules	34	12	1		0.066		
4 - Gains	4	2			0.032		
SUBTOTAL	66	18	3		0.166		0.166
BIT							
5301 Self Test	186	10	2	0.364			
Power Supply	48	6	1	0.076			
Data Exchange	28	1	1	0.047			
Memory Sum Checks	54	3	1		Initialization		
Discrete Input Test	75	9	1		0.131		
Output Wrap-Arounds	130		1	0.218			
Servo Checks	887	12	5		Pre-Flight		
Sensor Checks	221	6	6		Pre-Flight		
SUBTOTAL	1679	51	19	0.705	0.131	0.705	0.131
Executive	500	20	50	1.27	1.27	1.27	1.27
TOTALS	7381	1500	316	8.882	8.902	8.446	8.902

TABLE 21. SUMMARY OF SIZING ESTIMATE (TRIPLE SYSTEM)

Function	Memory Requirements			Computation Time	
	Instr	Const	Spad	msec	Sample Rate
Executive	530	20	50	1.27	40
SAS	250	50	20	0.60	40
Autopilot	715	160	40	1.55/2	20
Auto pilot warning	75	20	5	0.20/2	20
Air data	700	100	55	2.20/2	20
BIT (in flight)	1,700	60	30	0.77	20
Mode logic	525	10	20	0.48/4	10
Inlet control system	3,300	1,080	112	2x2.8	40
Total	7.795	1,500	332	10.34	
Percent of capacity	58.5	73.2	32.4	41.4	

3.4.3.2 Allocation of Digital Processing Subsystem Performance Requirements to Hardware and Software Requirements--This allocation of requirements is determined by defining the interfaces between the data processing functions and the rest of the system (the fourth item in the previous list) and by defining the interfaces between the hardware and the software. Experience has shown that serious problems may arise if these interfaces are not well defined and documented. These interfaces between system components are often reflected in interfaces between data processor design engineers. A large part of the data processing systems design effort can be taken up in communications between engineers on these issues.

The goal of this methodology is a preliminary design of the COF system and the basis for an estimate of its costs. However, it must provide a basic design which can be subsequently extended to a detailed design. During preliminary design it is easy to commit errors of omission. These are very hard to discover in later stages of detailed design and are very expensive to correct if they remain undetected until field trials. Very often, after all of the trade-offs have been made, the selected preliminary design is taken as the basis for subsequent detailed design without careful reviews of all of the assumptions and technical factors that went into it. The preliminary or concept definition work is done primarily to arrive at significant trade-off decisions. There may be omissions, inconsistencies, and errors that will cause trouble later on in the process if the methodology does not lend itself to successive refinements. Also, a basis for the validation of the final configuration must be established early in the design. The approach outlined in Reference 33 incorporates procedures for avoiding these difficulties and has been adapted for ICDT as described in the following discussion.

The allocation of hardware and software data processing functions in this approach is based on the flow of control of processing rather than on the flow of data manipulated by the processing. This has been found to be effective for avionics systems because there the control structures generally are complicated, but the data structures are elementary. The interface between the hardware and software is, in this case, more naturally defined in terms of the control of the processing. The description of the data flow is done later.

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[33] E. R. Rang, "The Use of Finite State Machines for Describing and Validating Flight Control Systems," NAECON '80 Dayton, Ohio, May 1980, Vol. 1, pp. 347-353.

The control of the processing is described in terms of the states and substates of the system and the events that cause transitions in these states and substates. This description is done at two levels. First, an abstract description of the flow of control is made without reference to hardware or software. After all of the events and states of the integrated data processing functions have been defined, the control of flow that is to be done by software functions is specified to complement the selected hardware facilities. This procedure gives a precise description of how the software must control the processing of the data. Now the specification of the actual computations can be fitted in smoothly.

This approach for the design of avionic data processing facilities is practical since the required computations are relatively straightforward. There is not a complicated sharing of resources nor are there elaborate collections of expanding and contracting data that are often required in general data processing systems. The control and interrupt structures for avionics are not complicated. Usually a simple executive routine calls functions in a fixed periodic fashion. The control structure that is described by states and outside events manipulates the functions within that periodic executive. The approach is formalized and reviewed in greater detail and an example is provided in the following discussion.

3.4.3.2.1 The Finite State Formulation--A finite state machine is a device with a fixed finite set of internal storage elements whose states determine the state of the machine. When an input is received, the machine switches to a new state. The new state depends on the previous state of the machine and the particular input that was received. While any practical computing device has only a finite number of states, the concept has utility for detailed description only if the number of states is small. Fortunately, the data processing for avionics systems may be defined in terms of a small number of configurations. A formalization of this approach will be outlined by modifying the discussion in Reference 34.

1. Define the External Interface--An abstract machine or set of abstract machines that interact with the non-data processing part of the system and the controlling factors external to the data processing subsystem are defined. These are specified at the highest level by suppressing as much detail as possible. They are defined by listing all possible states of each machine and by listing all the external events that can make a change in the states. Tables giving the state changes caused by particular events are convenient means for representing these abstract finite state machines.

2. Define the System Structure--The next stage is to begin constructing a hierarchy of abstract machines, adding detail and design decisions. The split between software and hardware functions is now defined by finite state software machines interfacing with hardware items.

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[34] L. Robinson, The HDM Handbook, Vol. I: The Foundations of HDM, SRI-International Report on SRI Project 4828, Menlo Park, California, June 1979.

This defines in more detail how the states of the top-level machine are represented and how the events are defined and processed to cause the correct changes of state. It should be possible to formally verify that the resulting software and hardware correctly implement the top-level machine. The machines are still abstract in that no software implementation has been specified. Some items of hardware may have been chosen.

3. Complete the hierarchy of abstract machines--Now more detail is added to complete the functionality of the requirements by adding new layers of machines. These introduce substates or partitions of the top-level states. Some iteration back to stage 2 may be required. For avionics software, only two levels of machines have been found to be useful: the abstract system machine and its corresponding software component. Other machines for flight control modes, redundancy management, and such are used, but these are completely and directly implemented in software; no hierarchical representation has been found to be useful.

4. Define data flow--For the most part, stages 1 to 3 have been concerned with representing an appropriate control structure to make the resources of the system available when called by the events. In this stage, the details of the computations and the data are added. If everything has gone according to plan, the original requirements have been captured in complete detail. At this point a review of the whole system is made before design of the software begins.

5. Estimate performance and computer requirements--If the requirements are organized by the preceding stages, then the estimates, the detailed software design, and the coding will be done smoothly and reliably. The integrated control methodology ends with these estimates.

Each of the subsystems of flight control, navigation, weapon delivery, and effectiveness management will have a description of its states and the events that cause changes of states. These have been established from the earlier steps of ICDT.

3.4.3.2.2 Illustrative Application to Flight Controls--The illustrative example is about a hypothetical flight controller which is to provide commands for stability augmentation, pilot relief modes, and commands for the flight director bars. The modes in the pitch axis are to be:

- pitch attitude hold
- go-around
- altitude hold
- glideslope
- control wheel steering

and for the roll axis:

- wings level
- heading hold
- navigation
- approach

The yaw axis will get only a damping signal. The sensors are:

- yaw rate gyro
- vertical gyro
- compass
- altimeter
- VOR/LOC receiver
- glideslope receiver

Switches control the autopilot, the flight director engagements, and the modes and there are mechanical means for slewing the heading hold reference and for adjusting the altitude reference value. A switch is provided for disconnecting the system in emergency, another for initiating the go-around mode, and a third for engaging the control wheel steering mode. A basic requirement is that the autopilot can be engaged only if and when the flight director has been previously engaged.

We must now make these requirements more precise by adding details and design decisions when appropriate. The top-level abstract machine is defined by the engagements of the flight director and the autopilot. Thus, the states are:

0. flight director off, autopilot off
1. flight director on, autopilot off
2. flight director on, autopilot on
3. flight director on, autopilot on, control wheel steering on

In the control wheel steering mode, the servos are temporarily disengaged while the pilot maneuvers to a new pitch attitude, which is then held automatically when the switch is released. The events that can alter these states are caused by:

- the autopilot dump switch
- the control wheel switch
- the go-around switch
- the flight director switch
- the autopilot switch
- the vertical gyro invalid signal

The top-level abstract machine is then defined by its state transition table, Table 22. The entries in the table show the number of the state to which the present state is switched for the particular event. In drawing this table, we are adding detail to the requirements. For example, the go-around switch and the control wheel switch are to turn the flight director on if it is off.

Nothing has been specified about how the states are represented. The relation that the autopilot can be turned on only if the flight director is already on can be enforced by hardware (a mechanical linking of switches, for example) or by software. Some ambiguities must be cleared up. For example, when the go-around switch turns the flight director on, the system must know that the flight director switch has also been turned on.

TABLE 22. SYSTEM FINITE STATE MACHINE

State \ Event	Autopilot dump switch on	Go-around on	Control wheel switch on	Control wheel switch off (released)	Flight director switch on	Autopilot switch on	Autopilot switch off	Flight director switch off	Vertical gyro invalid	Start in state 0.
0. Flight director off Autopilot off	0	1	1	-	1	0	-	-	0	All servos disengaged
1. Flight director on Autopilot off	0	1	1	-	-	2	1	0	0	All servos disengaged
2. Flight director on Autopilot on	0	1	3	-	-	-	1	0	0	Pitch, roll, and yaw servos engaged
3. Flight director on Autopilot on Control wheel steering on	0	1	-	2	-	-	1	0	0	Pitch and roll servos disengaged

Now to make the hardware/software split in this simple system: Assume that the flight director switch is a momentary contact switch which gives a signal only when it is held in. Then the software must include a tiny finite state machine to record the status of the pilot's actions. Assume that this is also true for the autopilot switch. The software will also enforce the state definitions. With these decisions, the finite state machine that the software must implement is represented by Table 23. There is not much change from Table 22 because most things have been put into software. If the switches had been mechanically linked, then the events would not be independent and Table 23 would reflect this.

Nothing has yet been specified for the signals that are to be computed when the system is in each of the four top-level states. That comes on the next level of hierarchy. The modes that are engaged are controlled by the pitch axis logic machine and the roll axis logic machine. The hierarchy is illustrated in Figure 22. There will be further hardware/software decisions when details are added; they have minor impact on the system structure.

3.4.3.3 Data Processing Hardware Selection--It is now an easy task to use a capability data base on computers and peripheral hardware to help match the requirements on throughput, memory, and so on. This will provide a facsimile of the system from which size, weight, power, cost, and reliability of the data processing hardware may be estimated.

TABLE 23. TOP-LEVEL SOFTWARE SYSTEM MACHINE

State \ Event	Autopilot dump switch on	Go-around on	Control wheel switch on	Control wheel switch off	Flight director button on	Autopilot button on	Vertical gyro invalid	Start in state 0.
0. Flight director off Autopilot off	0	1	1	0	1	0	0	All servos disengaged
1. Flight director on Autopilot off	0	1	1	1	0	0	0	All servos disengaged
2. Flight director on Autopilot on	0	1	3	-	0	1	0	Pitch, roll, and yaw servos engaged
3. Flight director on Autopilot on Control wheel steering on	0	1	-	2	0	1	0	Pitch and roll servos disengaged

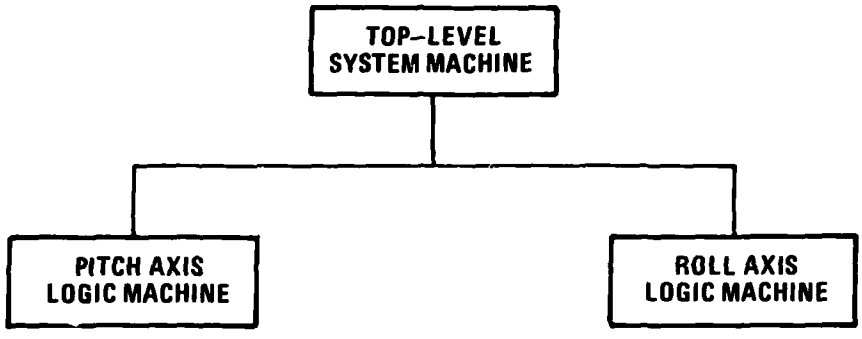

Figure 22. Hierarchy of Machines

3.4.3.4 Software Design--Most avionic software, particularly that used for flight controls, is not complicated. It is composed of a large number of simple functions, and the data structures are elementary. There are fixed sets of inputs, outputs, and state variables. The control of flow structure is direct with no complicated while-do loops. Few constructs of the complexity found in general software systems are necessary. This basic simplicity allows a methodology for specification and design that will facilitate the subsequent coding and verification.

The traditional approach has focused on the code itself, usually done in assembly language. Some attention was paid to top-down structure but not in any serious way. The simplicity of the problem permitted this approach. Even so, it has been found that more attention to specification and design pays dividends in verification, validation, and maintainability, thus saving considerably in life-cycle costs. While the ICDT methodology stops with preliminary design, that stage must be in a form which permits the detailed design to resume without much backtracking through the entire design process. Many new approaches are needed to software development. The first need is to incorporate the use of a programming language at a higher level than assembly language. The second need is to have the description of the specifications in a more precise form than the format provided for in part 1 of the design specifications. This precision is necessary to allow verification and validation to be made against a definite statement of the system requirement. While part 1 of the design specifications does well in describing for individual functions, it does not give a comprehensive picture of the global structure of the system that is sufficient for validation.

Our approach to the flight control software design builds on the finite state machine specifications described in an earlier subsection. This approach provides the global structure which is captured, along with the functional requirements, by pseudo code in a hierarchy-input-process-output (HIPO) format. The consistency of the input-output relations of the HIPO modules can be verified by hand or by formal machine procedures. Subsequent coding will proceed from the HIPO charts in high level language or assembly language, whichever is called for in the project. This is not part of the preliminary design methodology; we add this to show how the verification cycle may be completed.

The code may be verified against the HIPO charts, which in turn may be verified against the finite state machine description. This structure is highly visible; it is checked by review. The verification procedures can be made more explicit for special structures. For example, for flight controls the following groups of requirements must be established:

- The transitions and outputs of the system mode logic machines are correct.
- The computations of the control laws for each mode are correct.
- The data is correctly initialized and the state variables are preserved to the next computational cycle.
- The rate executive structure of calling the software modules for computation is correct.
- The data transfer between software modules is correct.

Considerations of verification and validation are central in a software methodology just as provisions for testing are central considerations in designing very large digital hardware configurations.

3.4.3.5 Estimation of Effectiveness of the Data Processing Hardware and Software--Hardware effectiveness may be estimated for the facsimile system chosen in subsection 3.4.3.3. An estimate of the reliability and maintainability may be made from data on previous systems using similar hardware. The performance may be reverified with the more detailed software/hardware configuration produced in the subsequent design efforts.

Software should be designed and verified to be correct. Since avionic software does not have the involved data and control structures of general software, this is not an unreasonable requirement. Data and control structures of avionic software should not have complicated interrupt levels. The software methodology should guarantee correctness. The newer methodologies make changes easier and more secure; this enhances maintainability and reduces life-cycle costs.

3.4.4 Subsystems Interfacing Design

At this point in the implementation part of the design methodology, the components for the non-data processing and the data processing subsystem have been selected. These components implement one or more functionally defined COF system candidate configurations. The software development has been carried through its preliminary design stage. Nothing has been done, however, about specifying the interfacing design that enables the subsystems and components to communicate with each other and to be controlled.

The selection of the components has been based primarily on how well they meet the performance (capability) requirements that have been decomposed from the mission/system level to the component level. As far as the reliability, maintainability, and survivability attributes have been considered, the selection of components has been based only on having maximum values of these characteristics once the performance requirements are satisfied. No prior decomposition of the values of these three attributes to the component level has been done to set minimum goals.

The objective of the interfacing design process, therefore, is not only to provide a communication link between the subsystems and components but also to upgrade the reliability, maintainability, and survivability of the integrated system by incorporating redundancy, reconfigurability, and survivability measures if and where necessary to meet the system level goals. This process is illustrated in Figure 23. The substeps within the implementation step of the design process are significant because they must ensure meeting three of the four attribute goals that combine to establish the system effectiveness goal. Performance, the fourth attribute, has been designed in at its required level during the functional design and the selection of components and it is assumed that the system's performance will not be degraded by the interfacing design. A failure that cannot be compensated for may occur, however, and cause the system to perform in a degraded operability state.

It should be noted that the interfacing design also provides the third opportunity for enhancing the integrated control design aspects of the system. The first opportunity occurs during the functional design when examinations can be made and judgments can be applied to reduce functional redundancy. The second opportunity occurs during the component selection when the availability and applicability of multifunction components (hardware and software) can be considered. This third opportunity is the application of integration considerations during the interfacing design in order to minimize the hardware and software necessary for the interfacing implementation.

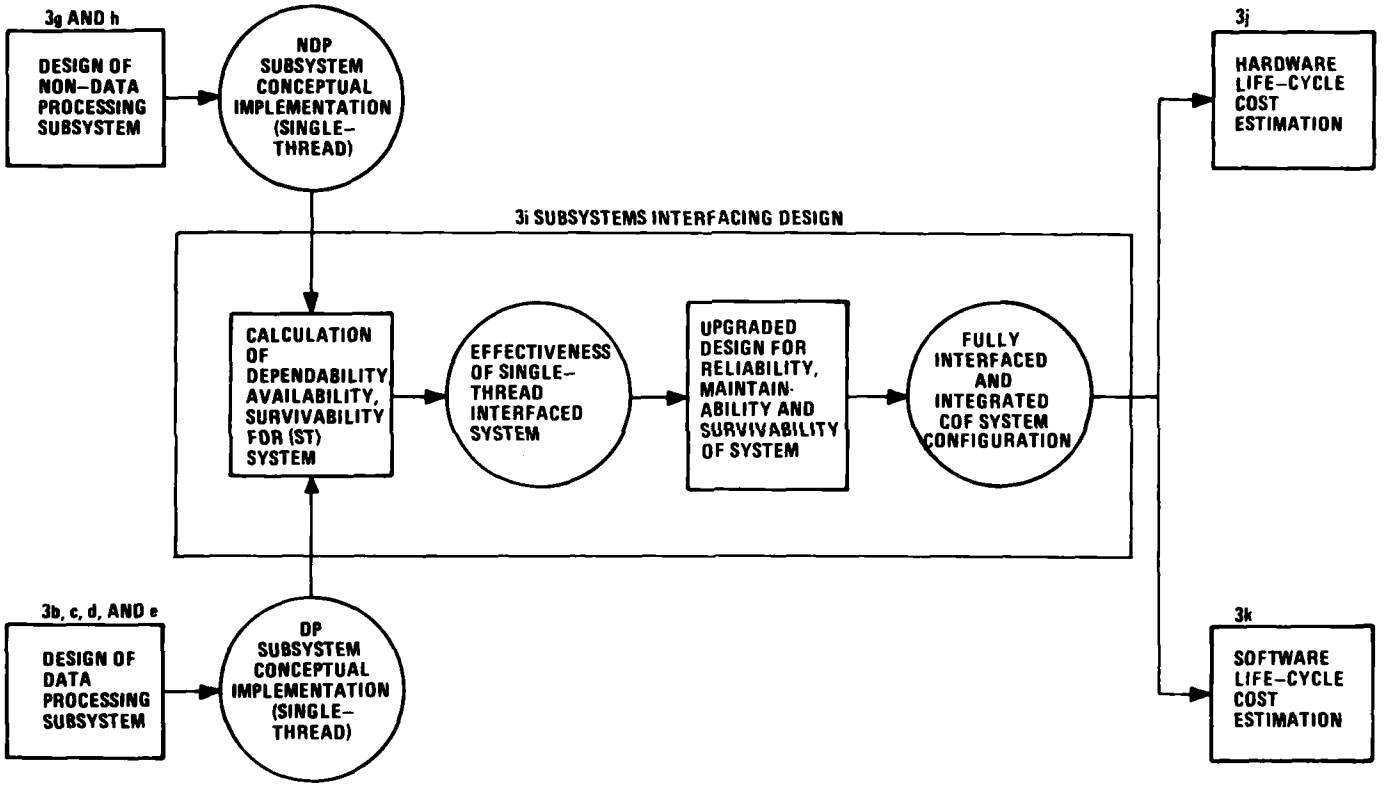

Figure 23. Expanded View of Subsystems Interfacing Design (Substep 3i)

Since the interfacing design substep is started with only the functional and decomposed performance requirements met and with the components selected primarily on the basis of performance, an iterative process will usually be required during the interfacing design to reach the system effectiveness goals. The first substep of the iterative process is to assume that the functional design and component selections that are the outputs of Step 2 and substeps 3e and 3h, respectively, are integrated only by a single-thread interfacing design plus a simple baseline maintenance plan and then to evaluate the reliability, maintainability, and survivability of this simple single-thread system. These values can be combined with performance values to get a system effectivensss estimate. If the evaluated effectiveness meets the mission/system level goal, which is not likely, the design is complete. If the effectiveness goal is not met, then the values achieved for reliability, maintainability, and survivability must be inspected and an analysis performed to see where and why the goals for these attributes were not met. This introspective analysis then provides the basis for the second substep in the interfacing design, which will incorporate whatever reliability, maintainability, and survivability measures (redundancy, reconfigurability, shielding, relocation, etc.) are expected to be necessary to meet the attribute's goals. This second substep will involve a significant trade-off study because the design parameters used to improve reliability and survivability will probably reduce maintainability, and a careful adjustment of the parameters will likely be necessary to meet all three goals simultaneously. Thus, it is highly likely that an

iteration of the interfacing design will be required to meet the system-level effectiveness goal. When the life-cycle cost (LCC) of the candidate system is subsequently evaluated, it may exceed the LCC goal and cause an additional iteration in either the component selection or the interfacing design substeps.

Brief descriptions of the tools and processes required to carry out the reliability, maintainability, and survivability evaluations and design upgrading are presented in the following subsections.

3.4.4.1 Reliability Evaluation and Design--The reliability evaluation tool recommended for the ICDT methodology is the System Effectiveness State Diagram Interpretive Program (SESIP) analytical model and program employing Markov modeling techniques which was developed by Honeywell. This is described in more detail in Reference 35 and in subsection 3.5. It is an efficient tool well suited to the concept definition level of COF system design.

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[35] J. Pukite, "System Effectiveness Modeling," presented at Computer Aids to System Effectiveness Institute, Milwaukee, Wisconsin, 20 May 1968.

The approach to designing additional reliability into the components and the interfacing subsystem has been selected to fit the ICDT design level; it is described in the following paragraph.

A reliability state model of the single-thread system is generated during the application of the SESIP tool to evaluate the system's reliability and dependability. With this state diagram, the primary sources of unreliability, or the areas of the single-thread system design where reliability can best be enhanced, can be identified. Then various redundancy techniques to make the system more fault tolerant must be considered and applied. These redundancy techniques can be applied either to the components selected or to the communication links that provide the interfacing of the single-thread system. The three main categories of redundancy techniques are static, dynamic, and hybrid. A description of these techniques and how they may be applied to improve reliability through fault tolerance is given in Reference 36.

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[36] A. Avizienis, "Fault Tolerant Systems," IEEE Transactions on Computers, Vol. C-25, No. 12, December 1976.

3.4.4.2 Maintainability Evaluation and Design--The technique for designing more maintainability into the system and for improving its availability is a two-step procedure. First, the components selected and the existing interfacing implementation are reconsidered for adjustments that will minimize mean time for detecting and repairing faults or failures. These adjustments could take the form of increasing component reliability or improving BITE. Then the maintenance plan can be adjusted to get a further increase in the availability attribute. These reconsiderations and adjustments are made using the system state diagrams. They must then be evaluated against the availability goal and repeated if the goal has not been reached. Section 3.5 provides models of maintenance plans that can be used to compute the availability of a system as well as its maintainability.

3.4.4.3 Survivability Evaluation and Design--The survivability evaluation tool recommended for the ICDT methodology is the survivable digital control (SUDIC) Quick Analysis model developed by Honeywell for the Navy (see Reference 37). It is described in more detail in subsection 3.5. It provides an evaluation of system survivability in the face of hostile action that includes small A^3 weapons. It can be extended to include other weapons by expanding its weaponry data base.

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[37] K.D. Graham, T.B. Cunningham, and Charles Shure, Aircraft Flight Control Survivability Through Use of On-Board Digital Computers: A Design Guide, Vol. 1, NADC-77028-30, Washington, D.C.: Naval Air Systems Command, May 1980.

The approach recommended for designing survivability into a system is described below. This approach encompasses the use of redundancy, reconfiguration, relocation, and shielding as techniques for improving survivability. The reconfiguration aspect of the survivability design is also an integral part of the implementation design for the effectiveness management function described in subsection 3.2.2.2.4.

With the partially interfaced system design resulting from the incorporation of reliability and maintainability measures into the single-thread system, the first step taken in the survivability design is dispersion of the system's components. The approaches to effective dispersion and the ways of estimating the resulting increments to the system survivability are described in the SUDIC report.

The next survivability measure to be considered is the incorporation of system reconfigurability techniques. A detailed description of an approach to designing reconfigurability into a flight control system is also described in Reference 37. This approach is applicable to COF systems as well as to flight control subsystems and is recommended for ICDT. Basically the COF system reconfiguration is accomplished through identification of faults or damage within the system and the application of effectiveness management logic to switch functions (wholly or partially) to undamaged components and to reconfigure flight control functions, if necessary.

The fault or damage detection and isolation aspects of reconfigurability design are much the same as those for reliability design. The reconfigurability design, however, permits recovery from the fault or damage by switching functions to undamaged components that are not redundant. Those components, which perform other functions, can be used as backup components. The backup components restore part or all of the function lost because of the failure or damage. Reconfiguration decision criteria are needed for developing the switching (effectiveness management) logic and for modifying the flight control laws, if necessary. The methods for developing these criteria are described in Reference 37. Once the criteria are selected, the effectiveness management logic for switching the functions can be derived and used in the functional design of the effectiveness management system (see subsection 3.3.2.5).

The next survivability measure to be considered, if the dispersion and reconfigurability design steps do not provide an increment sufficient to meet the COF system survivability goal, is the protection of components by shielding or hardening and the clustering of components as described in Reference 37.

If survivability is still lacking after the increments from all these techniques have been evaluated, an iteration of the redundancy design for reliability and/or of the various approaches to survivability design must be undertaken. The order in which these approaches are iterated should be selected by the system designer on the basis of their relative effectiveness as noted during their first applications.

3.4.5 LCC Estimation Techniques

In order for the LCC estimation technique for ICDT to be consistent with the concept definition level of system design, it must be an efficient process and dependent only on those performance and design parameters that are quantified during concept definition.

To achieve an efficiency compatible with the rest of the ICDT techniques, a parametric LCC estimation technique is called for. (See References 38, 39, 40.) The parametric approach is one of four LCC estimation approaches identified in a current survey paper in Reference 38. These were:

- Parametric approach
- Analogy
- Engineering (build up) or accounting models
- Historical data

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[38] Richard W. Grim, "Financial Management of Avionics and Electronic Systems," Presented at NAECON '80, Dayton, Ohio, May 1980.

[39] E. Louis Wienecke, III, Erasmus E. Feltus, and Daniel V. Ferens, "The Avionics Laboratory Predictive Operations and Supports (ALPOS) Cost Model," Presented at NAECON '80, Dayton, Ohio, May 1980.

[40] Edward N. Dodson, "Life-Cycle Cost Analysis: Concepts and Procedures," AGARD Lecture Series No. 100 (Methodology for Control of Life-Cycle Costs for Avionic Systems), 1979.

The parametric approach requires cost estimating relationships (CERs) to make it predictive. CERs relate the dependent variables, which are the life-cycle cost elements, to the independent variables, which are the system design, production, and maintenance parameters. In Reference 38, the use of parametric techniques was identified as the best approach for making cost effectiveness trade-off studies early in a system development program. Reference 39 states that "early visibility of potentially excessive downstream" costs is required since investigations have shown that as much as seventy percent of the system LCC is determined by the end of concept definition studies as depicted in Figure 24.

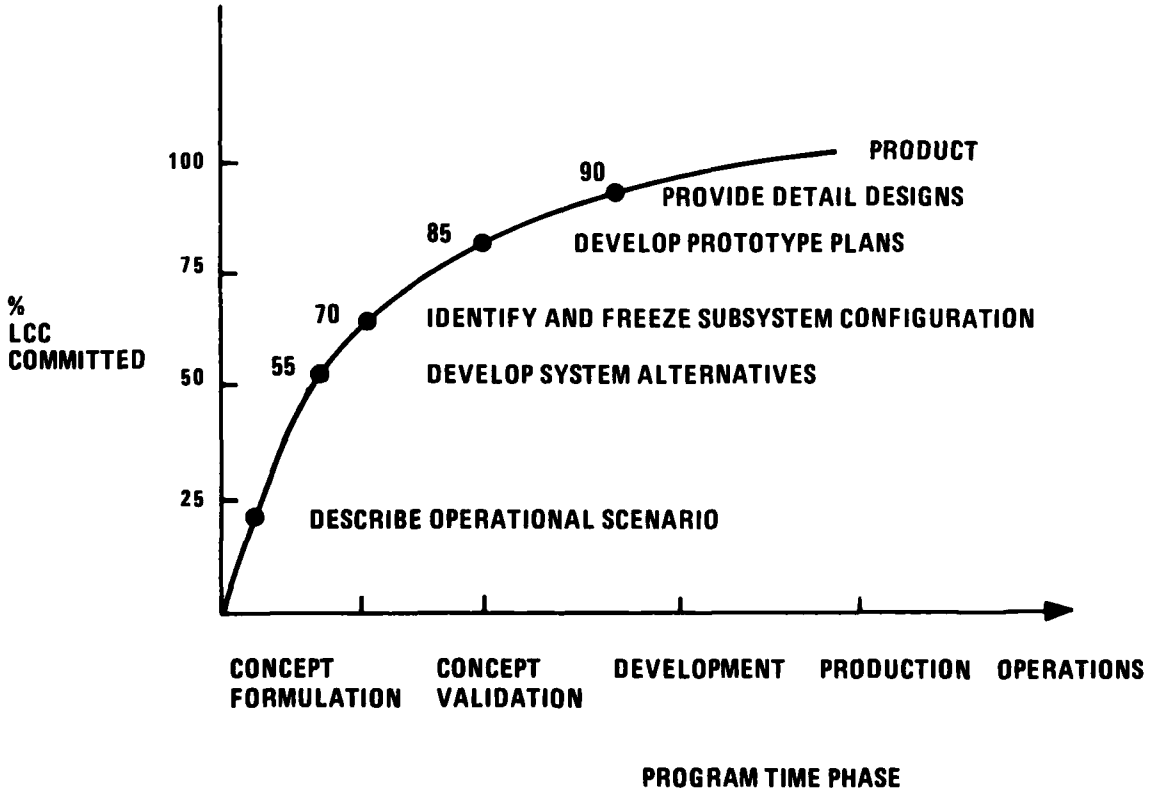

Figure 24. Percentage of System LCC vs. Program Time

Appreciation of this fact suggests that parametric techniques to predict LCC should be available in the conceptual phase. The following subsections describe a parametric LCC estimation technique that will fit the ICDT level of design methodology and will accommodate the early application objectives. The full implementation of this technique requires development of the CERs. This development is one of the future objectives of the ICDT program.

3.4.5.1 Technique Development--An LCC parametric estimation technique tailored to ICDT was developed because the existing techniques reviewed were not completely satisfactory. Recognizing that a system is almost always treated as two distinct subsystems, hardware and software, during the design and LCC estimating exercises and that the first level of cost decomposition is acquisition costs and operation and support costs, LCC techniques are usually classified as shown in Table 24 from Reference 38. The table also contains the names of some of the existing predictive techniques.

TABLE 24. EXISTING PREDICTIVE LCC ESTIMATION TECHNIQUES

	Acquisition Costs	Operation and Support Costs
Hardware	PRICE H	PRICE L ALPOS Save
Software	PRICE S Slim Wolverton Aerospace Model	Boeing CLMM GRC Model F-16 Model

The techniques listed above are useful but, in general, represent either an overly complicated or overly simplified LCC estimation process for the concept level definition of design.

The following derivation of an LCC estimation formula for ICDT is aimed at identifying an appropriate set of cost categories and cost parameters to cover design, production, and maintenance. The preliminary relationships between these cost categories and parameters are derived from and can be finalized by developing the CERs indicated. These CERs will be appropriate for doing cost vs design characteristics trade-offs at the concept definition level.

The first decomposition of LCC for ICDT is the practical and traditional split between hardware and software costs:

$$LCC_{ICSYS} = LCC_{HDWE} + LCC_{SFWE} \quad (1)$$

Next, the cost elements that make up a system LCC are considered. The most appropriate first level of decomposition is:

$$LCC = AQC + OSC \quad (2)$$

where,

AQC = system acquisition costs (not including spare or support equipment)

OSC = operating and support costs

The life cycle cost for ICDT can now be expressed as:

$$LCC_{ICSYS} = AQC_{HDWE} + OSC_{HDWE} + AQC_{SFWE} + OSC_{SFWE} \quad (3)$$

One further level of decomposition of these costs categories is necessary before they can be functionally related to the significant design, production, and maintenance parameters. These relationships identify the CERs that will have to be established to provide the concept definition level of LCC estimation methodology.

For hardware costs it is appropriate and has been traditional to break acquisition costs into these categories:

$$AQC_{HDWE} = RDC + PC$$

where, RDC = research and development costs (for the system)
PC = production costs of the initial number of operational units (10V) procured

and to break the hardware operating and support cost into these categories:

$$OSC_{HDWE} = TRLC + SC + DREC + OSOC$$

where, TRLC = test and repair labor costs
SC = spares costs
DREC = dedicated repair equipment costs
OSOC = operating and support overhead costs

The software acquisition costs (often referred to as software development costs in the literature) can be broken into categories that correspond to the phases of development as follows:

$$AQC_{SFWE} = RAC + FDC + DDC + VVC$$

where,

RAC = requirements analysis costs
FDC = functional design costs
DDC = detailed design costs
VVC = validation and verification costs

The software operating and support (O&S) costs are the least well known and understood. The breakdown into categories corresponding to phases of O&S, however, will be assumed as:

$$OSC_{SFWE} = FTC + REDC + RVVC$$

where, FTC = field test cost
REDC = redesign costs
RVVC = revalidation and verification costs

Now that all the cost components or dependent variables to be used in a concept definition LCC methodology have been identified, the independent variables to be used in the CERs must be identified. One problem with the dependent variable identification is, of course, that there are so many. Consequently, only the top-level variables, that is, those parameters that drive the costs significantly, are desired for concept definition work.

The cost drivers can be put into three groups for best association with the LCC cost categories. These groups are:

- Driving design parameters (DDP)
- Driving production parameters (DPP)
- Driving O&S parameters (DOSP)

Experience has shown that their primary influence, the top-level LCC cost categories, can be identified as follows:

$$AQC_{HDWE} = f(DDP, DPP)$$

$$OSC_{HDWE} = f(DOSP, DDP, DPP)$$

$$AQC_{SFWE} = f(DDP)$$

$$OSC_{SFWE} = f(DDP, DOSP)$$

Many studies for developing CERs have identified the driving parameters as follows:

DDP

- Weight
- Size
- Type (of system)
- Technology
- Complexity
- System Failure Rates (MTBF)

DPP

- Number of units initially ordered (NUI)
- Cost per unit of initial order (CUI)
- Production learning curve (PLC)

DOSP

- Maintenance and replacement policy (MRP)
- Spares provisioning policy (number of initial and piplem spares (SPP))
- O&S labor rates (LR)

- Design Experience Level (DEL)
- Number of line replaceable units per system (NLRU)
- System Repair rates (MTTR)
- Operating hours per month per system (OHM)

The tasks remaining for creation of the CERs are to identify for each dependent variable (the LCC cost categories) the independent variables (the cost parameters) that drive them significantly and to derive a specific functional relationship between them.

For the ICDT methodology a review of the existing parametric LCC estimation techniques has indicated that the CERs for the LCC categories will probably involve the following sets of driving parameters:

for AQC_{HDWE}

RDC = f(type, technology, complexity, DEL)

PC = CUI x NUI = f (weight, size, technology complexity, PLC) x NUI

for OSC_{HDWE}

TRLC = f(MRP, LR, NLRU, MTBF, MTTR, OHM)

SC = f(CUI, PLC, MRP, SPP, NLRU, OHM)

DREC = f(type, technology, complexity, MTBF, MRP, NLRU, OHM)

OSDC = f(MRP, SPP, LR, NUI, NLRU, OHM)

for AQC_{SFWE}

RAC = f(type, complexity, DEL)

FDC = f(type, technology, complexity, DEL)

DDC = f(type, technology, complexity, DEL)

VVC = f(type, complexity, DEL)

for OSC_{SFWE}

FTC = f(type, complexity, MRP)

REDC = f(type, technology, complexity, DEL, MRP)

RVVC = f(type, complexity, DEL, MRP)

These functional relationships (CERs) can be, and to some extent have been, derived by collecting significant samples of cost data and doing a regression analysis of it. In some cases CERs from other studies may be adopted and adapted to the ICDT LCC estimation methodology, particularly in the hardware categories. Two other options exist. The first of these is to collect the cost data and do regression analysis to derive CERs that fit the ICDT concept definition level of LCC estimation. The second of these is to adapt the ICDT methodology to utilize existing methodologies.

At present, any interim application of the ICDT methodology as developed (before the next phases of ICDM development which will cover data collection and implementation of the methodology flow) must depend on adopting existing LCC estimation methodologies, though they may not be efficient with respect to the concept definition level of design detail.

The following existing and nonproprietary methodologies are adopted for interim use:

	Acquistion Cost	Operation and Support Cost
Hardware	PRICE H	PRICE L or ALPOS*
Software	PRICE S	PRICE S3* or Boeing CLMM[41]

One further reflection on the development of an ICDT-tailored LCC estimation methodology is worth noting. The design driving parameter referred to as complexity has many facets. It may be necessary to develop parameter estimation relationships (PERs) that relate system effectiveness and performance parameters to the complexity parameter in order to properly scale the complexity of a system. For the ICDT methodology a breakdown of the anticipated cost-relatable (through complexity) performance and effectiveness parameters for the ICOF subsystems used in this study are shown in Table 25. Values of all of these parameters are established during a system design at the concept definition level.

3.5 SYSTEM EFFECTIVENESS EVALUATION PROCESS

3.5.1 Summary of Results

The WSEIAC methodology with modifications to include estimation of survivability and of pilot performance provides the model structure required for the ICDT effectiveness evaluation. The modifications include

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*When it becomes available

[41] Daniel V. Ferens and Robert L. Harris, "Avionics Computer Software Operation and Support Cost Estimation," Presented at NAECON '79, Dayton, Ohio, May 1979.

TABLE 25. COST-RELATABLE ICOF SUBSYSTEM PERFORMANCE AND EFFECTIVENESS PARAMETERS

Capability	Dependability	Availability	Survivability
Flight Control • Sensor accuracy • Stabilization response times • Number of command modes • Command mode response times • Algorithms required	• MTBF • Component redundancy	• MTBF • MTTR • BIT/FIT sophistication	• Component hardness • Component shielding • Component redundancy • Component spacing • Reconfiguration capability
Navigation • Sensor accuracy • Number aiding sensors • CEP performance • Number of steering modes • Type of modes • Algorithms required	Same parameters as above	Same parameters as above	Same parameters as above
Weapon Control • Sensor accuracy • Number of sensors • Sensor range • Sensor environmental capability • Tracking accuracy • Release time accuracy • Algorithms required	Same parameters as above	Same parameters as above	Same parameters as above
Effectiveness Management • Failure test points • Redundancy maintenance capability • Number of algorithms • Throughput and memory • Reconfiguration capability	Same parameters as above	Same parameters as above	Same parameters as above

- A derivative of the SUDIC model to be used to quantify survivability
- A new technique required to evaluate the effects of man-machine capability (pilot performance) on overall system effectiveness
- Hardware/software capability (performance) models that will be unique to ICDT.

Survivability was not included in the original WSEIAC methodology. Experience has shown that design for survivability is a very important consideration that can have an impact on both overall system performance and system cost. Since these two factors provide the evaluation impetus for the ICDM, survivability should be considered.

The same rationale also applies to the man-machine design. The work completed to date to incorporate pilot performance into the system effectiveness (SE) evaluation process was found to be either too cumbersome (pilot work load estimation) or incomplete (that is, performance factor stated in the SE model without adequate substantiation of the performance number defined). Thus the model required additional man-machine consideration.

The third point above refers to the system design configuration and is unique to a fully integrated control design. A fully integrated design by definition will share components to implement the required system functions. Past design configurations generally have each system function implemented independently of the other, that is, the navigation subsystem is completely independent of the flight control subsystem. This permits system effectiveness

evaluation at the subsystem level rather than at the component level because of the complete correlation of a particular set of components to a system function.

On the other hand, in a fully integrated design one component, such as a gyro or computer, may be shared by two system functions such as navigation and flight control. The effectiveness evaluation process, therefore, must carefully consider the component/system functional relationship in establishing the system states (that is, the operational, degraded, and failed states of the system). A detailed discussion of the evaluation process recommended is given below.

3.5.2 Model Requirements

Generic system effectiveness evaluation model requirements were first defined to guide the model definition task:

- The effectiveness evaluation process shall substantiate the selected design on the basis of mission performance.
- In scope and level of detail the evaluation process shall be consistent with the data available during the concept definition phase.
- The evaluation process shall be applicable to a digital integrated control system design methodology and to new aspects of system design using hardware and software for:
  --reconfiguration and redundancy management
  --fault isolation
  --fault tolerance.

- The evaluation process shall provide the capability to identify areas of inadequacy in system design and design/cost drivers, such as:
  --reliability
  --maintainability
  --mission effectiveness (availability, dependability, survivability, capability).
- The evaluation process shall be modeled for flexibility, growth, and expansion (adding flight management features).
- The evaluation process shall be realistic and manageable with respect to applying it at the concept definition level.

A general procedure and modeling tasks to meet the above requirements are summarized below.

- A procedure shall be established to define and relate the mission goals (selection criteria) to the system design parameters.
- Accordingly, within the procedure defined above, a model shall be defined that relates the system attributes to availability, dependability, survivability, and capability design (man-hardware and software) and to logistic system.
- A modular approach shall be used to provide program flexibility and growth.

The effectiveness evaluation procedure and a model that satisfies the above requirements is defined in the following subsections.

3.5.3 Process Flow/Steps

As stated in the summary of results above, the WSEIAC methodology, with the recommended modifications, will form the basis for the evaluation model. Included in this methodology is a description of tasks or procedures required to evaluate the effectiveness of a system. The eight tasks are defined as follows:

1. Define mission objectives (from problem definition)
2. Describe system states (from candidate system synthesis)
3. Specify figure of merit(s) (FOM)
4. Identify accountable factors
5. Select model
6. Acquire data (from data bank)
7. Estimate model parameters
8. Exercise model

These eight tasks are essential to the effectiveness evaluation of candidate systems as a part of the integrated control design methodology (ICDM). Two of these tasks are accomplished during Steps 1 and 2 of the ICDM design methodology. Reference 15 describes the intent of each task. The specific intent of each task for the ICDM is described below. The required inputs, outputs generated, and activity flow are shown in Figure 25.

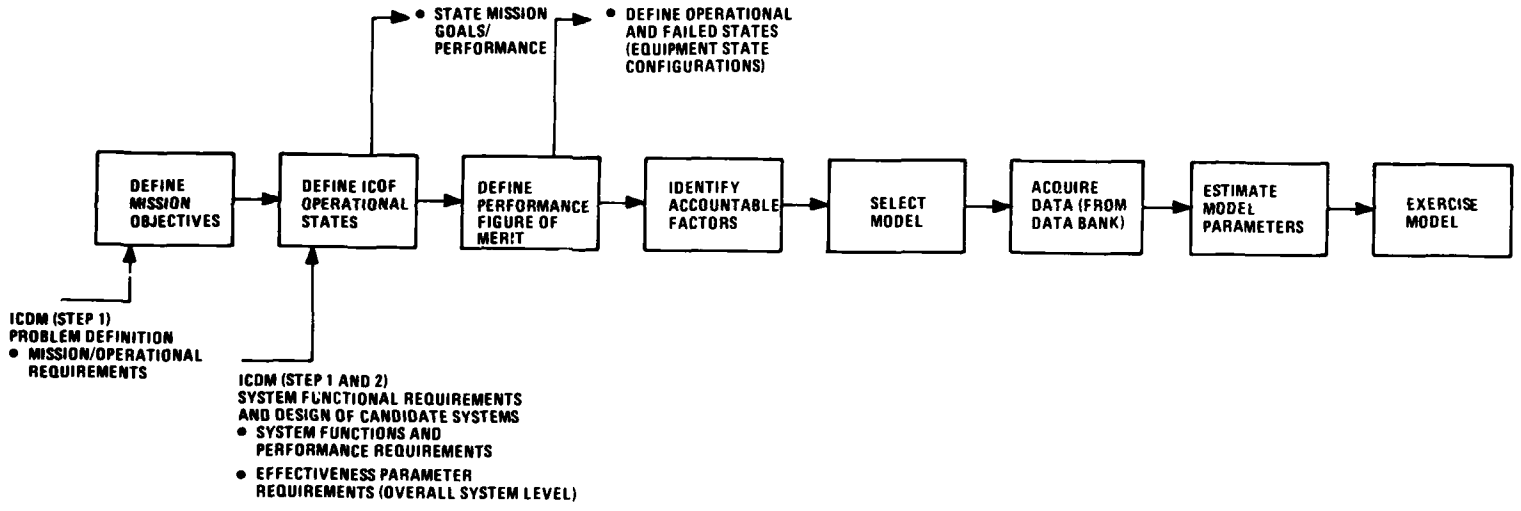


Figure 25. Eight Steps to an Effectiveness Evaluation of ICOF Candidate Systems

3.5.3.1 Definition of Mission Objectives--The mission objective definition is a precise statement of the intended purpose(s) of the system, of the environmental conditions (natural and man-made) and of the threat(s) under which it is required to operate. An example of a mission objective statement might read as follows: to penetrate enemy defenses and kill long range enemy gun emplacements with a probability of kill of 0.75 per sortie. Environmental conditions might be:

- Day/night operations
- 500 foot ceiling, 3000 foot visibility
- 50 mm, 4 quad enemy defense

This brief description establishes the measure of effectiveness as a kill probability and establishes the model input requirements, that is, the environment and threat conditions.

3.5.3.2 Definition of ICOF Operational States--The objective of this task is to establish the relationship between the fully operational system and the mission objective(s). Inputs from Steps 1, 2, and 3 of the ICDM will be required for accomplishing this objective. Task activity will include:

1. System description--Acquire a detailed understanding of the candidate ICOF system designs and their functions as defined in Step 3 of the classical steps for ICDM.
2. Mission profiles--Acquire established mission time lines showing the sequences of principal events from initiation of each mission to completion. The principal events should be correlated with both the mission segment and system functions defined above. Data provided from Steps 1 and 2 of the five classical steps for

ICDM will be used as inputs. This delineation will split the mission into a number of discrete time intervals during which different functions are being performed.

3. Mission event outcomes--Define the qualitative and quantative measure of the complete mission (kill enemy gun emplacements) and intermediate outcomes of the principal events defined above. An example of a principal event might include the joint event of flying below 300 feet and navigating to a check point within a CEP = 100m over a distance of 25 km.

4. System state diagram--Correlate the operational hardware with the system functions that must be performed within the mission segments (profile) to accomplish the desired mission outcomes. The mission state diagram identifies the components used to perform the functions within each mission segment along with their contribution to mission success. In addition, the system state diagrams will account for new system design techniques using hardware and software such as reconfiguration and redundancy management, fault isolation, and fault tolerance which will permit the system to operate in an alternate state of equal or degraded performance.

In summary, this task establishes the relationship between the system elements, their state of operability, and mission outcomes. This is essential in structuring an effectiveness evaluation model.

3.5.3.3 Specification of Figure(s) of Merit (FOM)--Figure(s) of merit serve to quantify what is expected of the system. They must be in an operationally-oriented form that can be readily understood and utilized in planning. An FOM usually corresponds to the mission outcome (which is significantly different from a hardware performance) and is defined as the probability of a successful outcome. The specified FOM(s) define a system effectiveness vector. For example, for the mission objective defined in subsection 3.5.3.1, the desired outcome is to kill (put out of commission) large gun emplacements. The probability of kill (0.75) is the desired measure or effectiveness of the system in accomplishing this mission outcome. For the ICDM the FOM will be limited to a single mission objective so that the effectiveness measure is a scalar quantity.

3.5.3.4 Identification of Accountable Factors--Accountable factors are those driving factors which are known or suspected to have a significant influence on the figure(s) of merit selected for the system effectiveness evaluation. All assumptions which are made in regard to these factors must be explicitly stated. Since the ICD methodology is to be used specifically in the planning phase and for concept definition, it is essential to preface all effectiveness analysis with a list of the assumptions concerning--

- The intrinsic failure and repair characteristics of the components (for example, exponential distributions, extrapolation techniques)
- The maintenance policies in effect (for example, preventive maintenance schedules, checkout procedures), and
- The environmental conditions under which the system is to operate (for example, temperature extremes, vibration, enemy countermeasures, etc.).

In addition, parametric studies to investigate the sensitivity of these factors shall be based on realistic excursions established by the verification of the assumptions made above. Table 26 is a checklist for identification of accountalbe factors for the ICDM.

3.5.3.5 Construction of Model--The model describes the system attributes required and how they will be combined to predict/estimate system effectiveness (FOM). The basic model selected for ICDM is shown in Figure 26. It is based on the model structure established by WSEIAC with a modification to include the attribute of survivability and the impact of the man-machine interface in terms of pilot response. Model descriptions will be given in subsection 3.5.4.

3.5.3.6 Acquisition of Data--The importance of establishing a data base for the ICDM is clear. The accountable factors as indicated in subsection 3.5.3.4 and the inputs required for the models as indicated in subsection 3.5.4 define the data element requirements. Data element requirements must be clearly stated to correspond to the level of detail specified by the models. Sources of data, methods of collection and extrapolation, and format must be clearly defined. The completeness, the appropriateness, and the compatibility of available sources of data constitute the largest cause for differences in the evaluation of effectiveness from one development stage to another in the system life. During the conceptual stage, for which the ICD methodology is being developed, heavy reliance must be placed on generic data for component and subsystem characteristics, on results learned from similar systems, and on application of basic knowledge about the physical laws appropriate to the system concept. This information can be used in the parameter estimation task defined below.

TABLE 26. CHECKLIST FOR IDENTIFICATION OF ACCOUNTABLE FACTORS

System Hardware Description
- Modes of operation
- Hardware organization
- Software organization

Compatibility

(e.g., Electromagnetic compatibility)

Survivability

Vulnerability

Deployment

Geographic Factors
- Deployment
- Geology
- Climate
- Atmospheric phenomena

Personnel
- Operating
- Maintenance

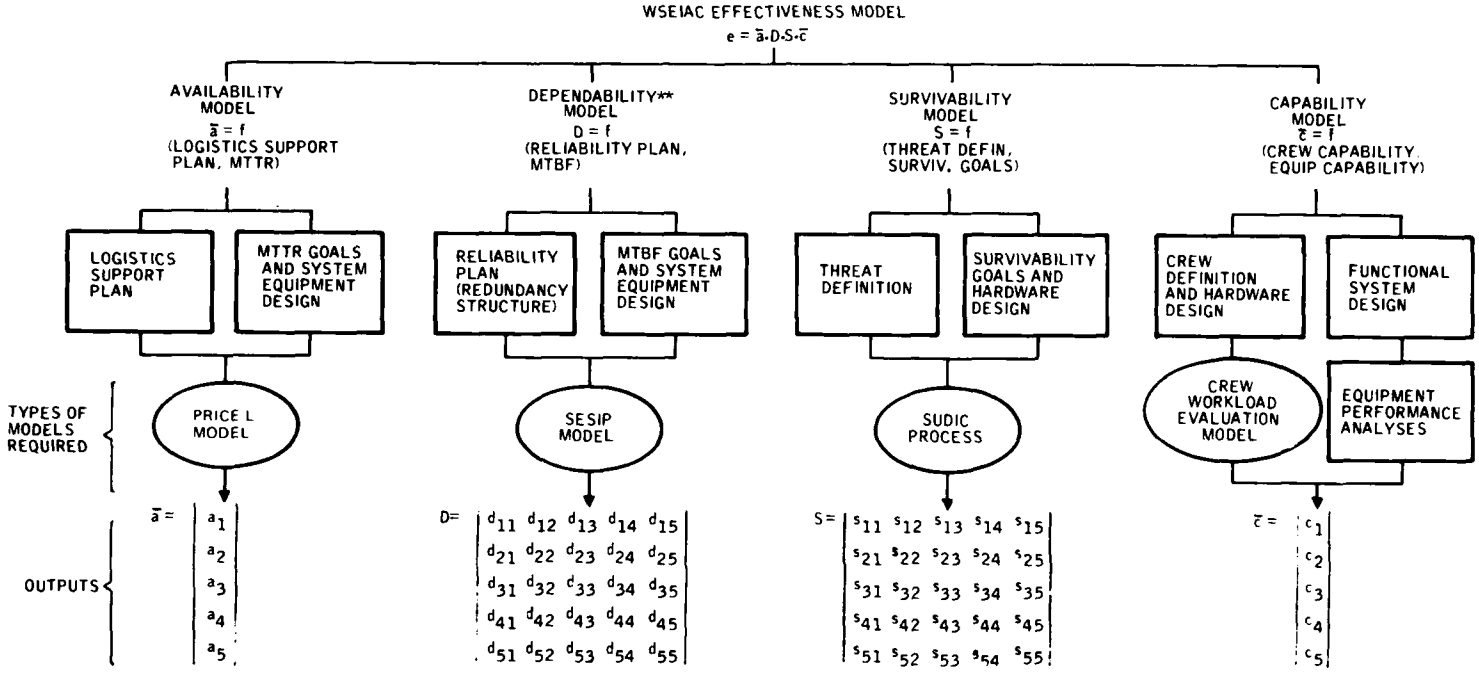
Spares
- Provisioning
- Storage
- Packaging

Transportation

Support Equipment
- Test
- Transport
- Maintenance
- Facilities

Procedures/Policies
- Operating
- Repair
- Inspection/Maintenance
- Testing

System Interfaces
- Support systems
- Force mix
- Strategic Integrated operations Plan (SIOP)



NOTES:

PRICE L MODEL CAN BE USED TO SPECIFY LOGISTICS SUPPORT STRUCTURE
DATA IN BOXES MUST BE INPUTS FROM DESIGN PROCESS

* ICOF FOR THIS PROPOSAL DISCUSSION MEANS ALL THE PRIMARY AVIONIC SYSTEMS, BOTH AUTOMATIC AND PILOT IN THE LOOP, THAT ARE NEEDED FOR THE MANAGEMENT OF THE AIRCRAFT AND ITS MISSION.

** SAFETY WILL BE CONSIDERED INITIALLY AS A SUBSET OF DEPENDABILITY

Figure 26. System Effectiveness Evaluation Model Structure for ICOF Systems

3.5.3.7 Estimation of Parameters--Processing the data elements to derive numerical estimates for the parameters required in the models is the next task. The analytical techniques used to reduce the data are referred to as parameter estimation techniques. The specific methods will depend upon:

- The nature of the parameter being estimated
- Available data
- The format of data collection.

As previously stated the ICDM is to be used as a planning tool in the early concept definition phase. Extrapolation techniques must be used in parameter estimation, because there will be no experimental data on the system being synthesized.

3.5.3.8 Exercise of Model--The system effectiveness vector (scalar in the case of ICDM) is now calculated using the model equations and parameter inputs. This is an iterative process in which variations in accountable factors will be made to determine parameter sensitivity either locally, on each attribute, or globally, on total system effectiveness. This process is discussed in more detail in subsection 3.5.4, Model Description. Reference 15 (pp 17-21) provides additional discussion of the eight tasks listed above and how they differ during the four major system phases: (1) Conceptual phase, (2) Definition phase, (3) Acquisition phase, and (4) Operational phase.

3.5.4 Model Description

The system effectiveness evaluation model selected for ICDM is shown in Figure 26. This model is based on the guidelines provided by the WSEIAC reports with modifications to include evaluation of system survivability and the impact of the man-machine interface. This model was selected because it meets all the requirements defined in subsection 3.5.2, and it is particularly well suited for use during the conceptual phase of a system development.

First of all, the guidelines provided by WSEIAC stress the importance of relating effectiveness to the mission objectives. In this way there is a quantitative functional relationship between the mission objective and system design (including the maintenance and logistic structure). This provides a better understanding of the design drivers and data to substantiate design decisions.

Secondly, the WSEIAC guidelines recognize that during the conceptual phase little detail will normally be available describing the specific hardware and software elements of the system. It therefore provides for parameter estimating techniques and probability theory to compute the different system attributes (that is, availability, dependability, etc.).

Thirdly, the WSEIAC model approach is flexible and allows for new design techniques for reconfiguration, fault isolation, and fault tolerance. The level of detail provided by the model and its flexibility permit detailed sensitivity studies to identify areas of inadequacies in system design. And finally, an analytic approach (as opposed to a Monte Carlo simulation) is used which provides a realistic and manageable evaluation process.

The effectiveness evaluation model overview is shown in Figure 27. The cost model is shown because it will provide estimates of equipment (component) MTBFs and individual availabilities (α_i's) required to compute the dependability and availability matrix elements. The decision is based on the high degree of interaction between equipment design, reliability, logistics, maintenance concept, availability, and support costs.

The cost models are discussed in more detail in subsection 3.4.5. The PRICE (Programmed Review of Information for Costing and Evaluation) models are shown as an interim to the recommended model. The PRICE Models[42] are a family of three cost-estimating models: (1) basic PRICE model, which estimates development and production cost of hardware, (2) PRICE L, which provides maintenance and support costs of hardware products and systems, and (3) PRICE S, providing for design, implementation, and test costs of all types of deliverable computer software. A description

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[42] M.H. Burmesiter, "Parametric Analysis of Design to Life Cycle Cost," from Price Systems RCA Corporation, Cherry Hill, N.J., Published in Proceedings of the IEEE 1980 National Aerospace and Electronics Conference, NAECON '80, May 1980 (pp. 675-681), Vol. I.

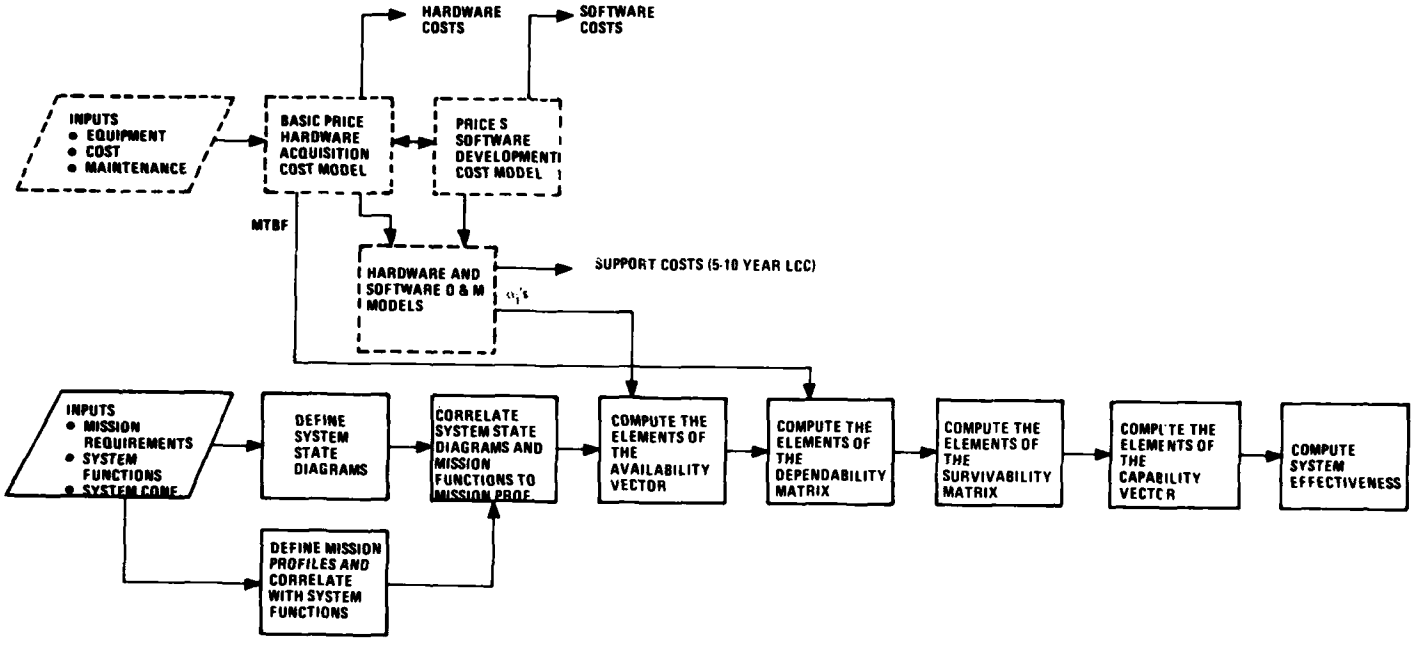

Figure 27. Effectiveness Evaluation Model for ICDM

of the PRICE models here is beyond the scope of this report. In summary, PRICE includes all the important accountable factors required to estimate MTBF's and individual equipment or component availabilities. For example, the PRICE L model examines deployment and employment, sorts through 28 different maintenance concepts, and automatically selects the most cost-effective maintenance concept. In addition to cost, the PRICE models output equipment predicted field MTBF, operational availability, and operational readiness as a function of maintenance concepts which are used to compute the dependability matrix and availability vector respectively. The PRICE model was selected primarily because it is the most up-to-date model widely used in the U.S. Government and industrial circles. PLANET is a Monte Carlo simulation of availability for multiple aircraft systems, given demand rates, failure rates, and logistic support parameters. Set up time and cost to run such a model did not meet the model requirements defined for ICDM. GEMM is in many ways similar to PRICE but was judged to be somewhat out-of-date. The model would have to be updated to include software design considerations.

3.5.4.1 Model Inputs--Model inputs required to initiate the effectiveness evaluation of candidate ICOF systems are derived from ICDM Steps 1 through 3. The basic inputs include:

- Mission requirements and performance goals
- System functions
- System configuration/description

These inputs to the eight tasks defined in the effectiveness evaluation process (subsection 3.5.3) will establish model inputs and configuration to perform the multiple runs required for systems evaluation and trade studies. A detailed discussion of the ICDM effectiveness evaluation model is provided below.

3.5.4.2 System State Diagrams--System state diagrams define the operating states of the system (that is, what equipment is on or failed and what system function is impacted). State diagram formulation is extremely important because it dictates how the calculations of the individual effectiveness attributes of availability, dependability, survivability and capability must be structured. For ICDT the following diagram formulation procedures will be used.

- A system state defines equipment that is operating or failed and either provides full, degraded, or zero performance for one or several system functions.
- A software program will be treated like hardware. Both hardware and software must be operating if required for a specific function.
- State transitions must be possible for either failed states or repaired states.

A system state diagram applicable to all possible ICOF configurations is not proposed at this time. State diagrams are highly dependent upon the mission and system configured to meet mission requirements. However, this may change after the ICDM has been applied, when it can be shown that one generalized model may satisfy all ICOF configurations where some states are empty for some systems.

3.5.4.3 Mission Profile/System Function Model--The mission model and system functions are correlated through the use of a time line which defines discrete mission segments and system functions required to meet each segment requirements. This process and the results will be illustrated in subsection 3.5.5.

3.5.4.4 Mission/System Model--System state diagrams are correlated to the mission profiles to establish the mission/system elements to the effectiveness evaluation models. This process and resulting model will be illustrated in subsection 3.5.5.

3.5.4.5 Availability Model--The WSEIAC availability model structure was selected as part of the effectiveness evaluation for ICDM. This model is defined in detail in Reference 15. A summary description of the model is given below.

First of all, by definition, availability is a measure of the system condition (repaired or failed) at the start of a mission, when the mission is called for at an unknown (random) point in time. There are other terms used to describe the system state at the beginning of a mission. For example, one concept of operational readiness includes calendar time while availability includes only desired use time. For the ICDM, "Availability is the probability that the system will operate satisfactorily at any point in time when used under stated conditions."[43] The availability of any one unit

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[43]See Reference 15.

in the system is given by:

$$\alpha_i = \frac{MTBF(i)}{MTBF(i) + MDT(i)}$$

where MTBF(i) = the meantime to failure of unit i

MDT(i) = the meantime to repair the unit i

MDT(i) is highly dependent upon both the system design and the maintenance concept. MDT must therefore be determined using a logistic/maintenance model. Having the availabilities for the individual units (modules, components, equipment), we can then compute the system availability vector $\bar{A}$.

The system availability is defined by a vector, $\bar{A}$, which is a row vector $[a_1, \quad , a_N]$ containing the probabilities of the various defined system states when the mission begins. This vector will be computed from the individual unit availabilities using probability theory, that is, a_i is the product of the α_i's and $(1-\alpha_i)$'s (or unavailabilities). For example if a_i is defined as the probability that all N-units are available

$$a_i = \prod_{i=1}^{N} \alpha_i$$

Also if a_2 is defined as the system state where component 1(i=1) is not available

$$a_2 = (1-\alpha_1) \prod_{i=2}^{N} \alpha_i$$

This process of combining the α_i's according to the state diagram model will continue until all states are accounted for and the availability vector $\bar{A}$ is defined. This process and the model structure will be illustrated in subsection 3.5.5.

3.5.4.6 Dependability Model--The WSEIAC dependability model structure was selected as part of the effectiveness evaluation for ICDM. This model is defined in detail in Reference 15. A summary description of the model is given below.

By definition, dependability is a measure of the system's condition during the mission. Two possible concepts exist: (1) no in-flight repair, that is, if a system fails it remains in the failed state until the aircraft returns to base for repair or (2) in-flight repair in which the system can be restored to one of its operational states. Note that the later does not include any automatic reconfiguration or redundancy since these will be considered in the system state diagram.

In the first concept the aircraft will either continue in a degraded but acceptable state or return to base. The second concept implies that a system has been designed for in-flight repairability and, although such actions must remain simple, does provide for capability of restoring the system to a former operational state. The dependability model proposed for ICDM includes in-flight repairability as structured in the WSEIAC reports. Thus dependability is the probability that the effective state of the system during the mission is j, given that the mission was initiated in state i and providing that a downtime per failure not exceeding a given lapse time (t) will not adversely affect the overall mission success.

From Reference 15, system dependability is represented as a matrix

$$[D] = \begin{bmatrix} d_{11}\ d_{12} \cdots\cdots d_{1n} \\ d_{n1}\ d_{n2} \cdots\cdots d_{nn} \end{bmatrix}$$

where

d_{ij}'s - are the probabilities that the system will be in state j at the end of a mission, given that it was initially in state i

and

$$\sum_{j=1}^{n} d_{ij} = 1 \quad , \ i = 1,2,\ldots\ldots, n$$

n = number of system states

The specific formulation of the dependability matrix depends upon the effect of the failures during the mission and whether or not repair is possible during the mission.

A simple example will be used to explain the dependability model. The system consists of one piece of equipment that must be in one of the two states at the time of mission demand: namely, operable or failed. Thus, we consider a 2 x 2 matrix:

$$[D] = \begin{bmatrix} d_{11} & d_{12} \\ d_{21} & d_{22} \end{bmatrix}$$

where the d_{ij}'s have the following interpretations:

d_{11} = The probability that the system is operable at the end of the mission, given that it was operable at start of the mission.

d_{12} = The probability that the system is failed at the end of the mission, given that it was operable at the start of the mission

d_{21} = The probability that the system is operable at the end of the mission, given that it was failed at the start of the mission.

d_{22} = The probability that the system is failed at the end of the mission, given that it was failed at the start of the mission.

The model required to compute these probabilities is described below. Model assumptions are that times to failure after repair actions and times to repair after failures are exponentially distributed for the ICOF system. This means that the probability of a failure or a repair in a small increment of time (Δt) can be expressed as

- Probability of failure in time $\Delta t = \lambda \Delta t$
- Probability of a repair in time $\Delta t = \mu \Delta t$

where

λ = system failure rate

μ = system repair rate

With this assumption, the differential equation for the probability that the system will be in system state (1) is

$$\frac{d\,P_1(t)}{dt} = (\lambda + \mu)\,P_1(t) + \mu$$

The general solution to this differential equation is found to be

$$P_1(t) = \frac{\mu}{\lambda+\mu}\left[\,1 - e^{-(\lambda+\mu)t}\,\right] + P_1(o)\,e^{-(\lambda+\mu)t}$$

where $P_1(o)$ is the probability that the system is operable at $t = o$. By difinition $P_1(o) = 1$ at $t = o$, then d_{11} is the value of $P_1(T)$ when $P_1(o) = 1$, and d_{21} is the value of $P_1(T)$ when $P_1(o) = o$, where T is the duration of the mission. Thus

$$d_{11} = \frac{\mu}{\lambda+\mu} + \frac{\lambda}{\lambda+\mu}\,e^{-(\lambda+\mu)T}$$

$$d_{12} = 1 - d_{11}$$

$$= \frac{\lambda}{\lambda+\mu}\left(1-e^{-(\lambda+\mu)T}\right)$$

$$d_{21} = \frac{\lambda}{\lambda+\mu}\left[1-e^{-(\lambda+\mu)T}\right]$$

$$d_{22} = 1 - d_{21}$$

$$= \frac{\lambda}{\lambda+\mu} + \frac{\mu}{\lambda+\mu}\,e^{-(\lambda+\mu)T}$$

Now if we assume that in-flight repair is not used in the ICOF design, μ = o and the equations become

$$d_{11} = e^{-\lambda T}$$

$$d_{12} = 1 - e^{-\lambda T}$$

$$d_{21} = 0$$

$$d_{22} = 1$$

which are consistent with equations derived assuming no in-flight repairability.

The next step is to expand the dependability matrix to include an n-state system. This can be done by considering the dependability of each unit in the system state diagram and combining their probabilities according to the rules of statistics. A technique for computing these probabilities has been modeled in a program named SESIP (System Effectiveness State Diagram Interactive Program).[44] This model was developed by Honeywell for the government to facilitate the analysis of complex multiphase, multimode and multimission systems such as the ICOF system. The basic structure of the program is the same as that of the earlier SIP (State Diagram Interpretive Program) developed under Air Force contract AF 33(615)-2475.[45] Inputs to the program are the state diagram model with

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[44] J. M. Thuirer and L. L. Montague, SESIP Computer Program Documentation, March 1970.

[45] State Diagram Interpretive Program: A Guide for Users, U-ED 1600-1, December 1964. Revised, March 1966, by E.J. Daum, Honeywell, Inc.

indicated equipment failure rates and repair rates; the program then computes the elements of the dependability matrix. The program with appropriate inputs can also compute system availability and combine the three attributes of availability, dependability, and capability to compute systems effectiveness. It is recommended that the program be modified to include survivability which requires incorporation of another matrix multiplication. Program description is given in reference 44 and 45. The procedure as illustrated in the example problem is subsection 3.5.5.

3.5.4.7 Capability Model--Capability is a measure of the k^{th} figure of merit, conditional on the given system state j. Thus the element C_{jk} of the capability matrix is the k^{th} figure of merit (or mission objective) associated with system performance in system state j. For ICDT we will consider only one FOM and therefore C_j is a vector. The magnitude and dimensions attached to this figure of merit depend upon the specific nature of the system undergoing evaluation. For example, the ICOF system might be designed for an aircraft delivering weapons to within some specified miss distance. The calculation of each C_j could, in this case, require an accounting for the targeting policy, weapon dispersion, weapon sighting system, flight control, terrain avoidance, navigation, communication, IFF, instrumented landing, and the man-machine interface.

Because the C_j's depend so specifically on the type of system designed and mission to be performed, the capability model must be correlated to the system state diagram and the mission profile/system function profile defined for the system. This will be explained in more detail in the example given in subsection 3.5.5.

The proposed capability models for ICDM will consist of the performance models defined for the functional performance evaluation modified to include the pilot response input from the man-machine queuing model. Provisions shall be made to transform system capability to a probability of mission success.

3.5.4.7.1 Equipment Capabilities--As stated above the output of the functional (equipment) performance models defined in subsection 3.5.2 must be in terms of or converted to probabilities of success. For example, if the mission requirements are such that an aircraft must navigate to within x-feet of a checkpoint and this can only be accomplished 50 percent of the time with a selected navigation design, the probability of navigation success is .5. Thus the equipment capability models will be extremely dependent upon the definition of mission requirements and the method of computing equipment performance. In addition, the equipment performance models must consider modeling impact of pilot response delays, that is, the fraction of time the pilot may be delayed (because of work load) during the mission (for example, position accuracy degradation). Pilot delays shall be generated by the queuing model discussed below.

3.5.4.7.2 Pilot Queuing Model--A simplified queuing model is used for evaluating the impact of man-machine interfaces on ICDM performance during the concept definition phase. This conclusion is based upon a survey of existing analytical techniques for aircrew work load analysis and on judgment based on past experience with previous studies of this kind. The rationale for the conclusion is as follows:

1. Pilot work load models are system-detail orientated and require a lot of manual labor to set up.

2. Pilot work load models are cumbersome to manipulate and not conducive to fast turnaround in performing design trade-off studies.

3. Because we are addressing the concept definition phase, there will be no cockpit mock-ups to provide detail work load lapse times.

The analogy of queuing (or waiting line) to pilot activities is clear from the work load analysis models used in the past, (that is, considering the number of tasks, task times, and the amount of time available to do the tasks determined when the pilot was saturated). The primary difference, however, is in technique. Rather than use specific tasks, task times, etc., queuing theory uses probability density functions such as for a service facility during any specified time interval. The service facility in this case is the pilot at the controls of the aircraft. The average length of the waiting line establishes the response delay of the pilot in performing the required system actions.

A simple example, using the queuing method described in Reference 46 will demonstrate the technique. Consider a sequence of tasks (messages) which must be performed on the average of once every 10 seconds (task arrivals) and with Poisson distribution:

$$P_T(n) = \frac{(\lambda T)^n e^{-\lambda T}}{n.^o}$$

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[46] Guidebook for Systems Analysis/Cost-Effectiveness, prepared for U.S. Army Electronics Command under Contract DAAB07-68-C-0056, March 1969.

where

$P_T(n)$ = probability of n-tasks (to be performed or in the process of being performed) in the system (pilot work load)

n = number of tasks in the system

$\lambda = \frac{1}{\bar{\tau}_a}$ = average arrival rate (sec^{-1})

$\bar{\tau}_a$ = average task arrival time

The service times for performing the tasks are assumed to be exponentially distributed:

$$P(\tau_s) = \mu e^{-\mu\tau}$$

where

$P(\tau_s)$ = service time distribution

$\mu = \frac{1}{\tau_s}$ = average service rate

τ_s = average service time for completing a task

If we assume that pilot performance can be expressed in terms of a probability of successfully completing a task and that this measure (P_c) can be expressed in terms of the average number of tasks (n_a) in the queue, we could, in fact, derive pilot performance using queuing theory techniques. For example, let us assume the following expression for pilot performance:

$$P_c = \frac{K_p}{n_a + 1}$$

where

P_c = probability of successfully completing all tasks

K_p = constant of proportionality

n_a = average number of tasks in the queue (either waiting to be performed or being performed)

The selection of K_p should be based on experimental data. In this case we will select $K_p = 2$ for $P_c = 1$ and $n_a = 1$. This says that if, on the average, there is only one (1) task in the queue, the probability of pilot success is one (1).

For this particular type of a queue the average number of tasks, n_a, in the system is given by:

$$n_a = \frac{2}{\mu - \lambda}$$

where

$$\lambda = \frac{1}{\tau_a}$$

$$\mu = \frac{1}{\tau_s}$$

For a given $\lambda = .1$, the average service times for performing the tasks can be studied parametrically. For example let $\tau_s = 8$ seconds, then

$$n_a = 4.0$$

Using the expression for pilot performance

$$P_c = 0.4$$

We can also compute the average delay (pilot response) resulting from the system queue. If t_s = 8 seconds and n_a = 4 we can expect, assuming all tasks must be performed, a task delay of 32 seconds (that is, $\tau = \tau_s \times n_a$). The results of this analysis provides an input to the equipment capability models which account for pilot delay (Figure 28).

If the pilot response and performance are not adequate, a system redesign to reduce either the task rate of arrival or task rate of service through automation or some other techniques can be examined.

3.5.4.7.3 Total System Capability--The total system capability is derived by combining the equipment capability (probabilities) and pilot capability (probability) for each possible system state, j = 1,2,... Figure 28 shows the analysis flow for three major system functions: flight control, navigation, and weapon control. Assuming a mission phase/equipment state in which all three major functions are required and in which the probability of flight control (P_{FC}), navigation (P_N) and weapon control (P_{WC}) along with pilot performance (P_C) are defined, the combined system capability for the j^{th} equipment state is given by:

$$C_j = P_{FC} \cdot P_N \cdot P_{WC} \cdot P_C$$

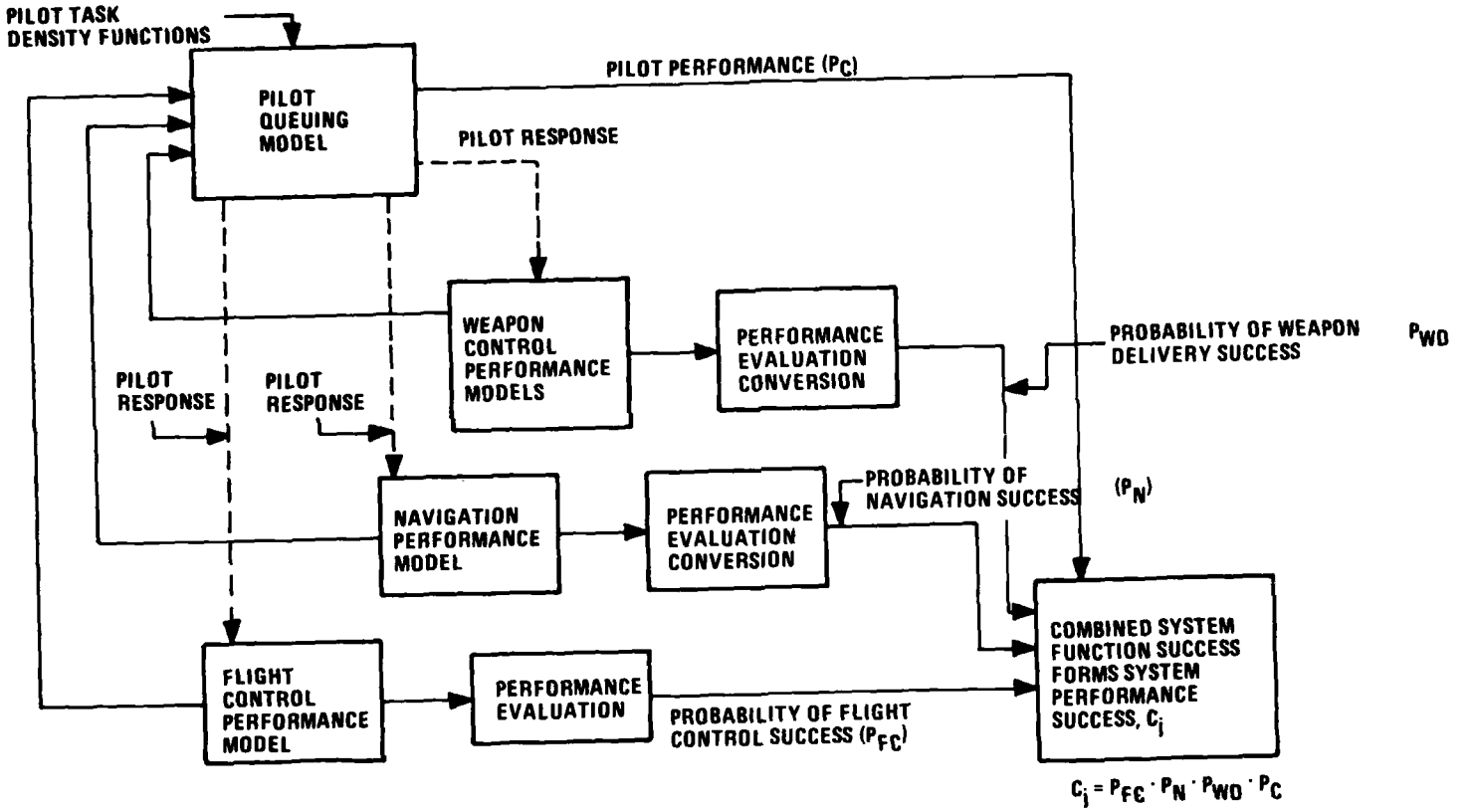

Figure 28. Capability Model

3.5.4.8 Survivability Model--The design of survivability for a control-of-flight system must take into account the structural and survivability design of the aircraft that the system is being designed to control. Likewise the quantitative evaluation of the survivability for a given COF design or configuration must include as inputs some aircraft geometric structural and performance characteristics. The approach to synthesizing the survivability aspect of the COF system to complement the aircraft's survivability design is described in Reference 37. The analysis of the survivability of the integrated system is a significant part of the iterative process that the complexity of survivability design requires. It is also part of the overall system effectiveness evaluation step. The model recommended for the ICDT methodology is described in the following subsections.

3.5.4.8.1 Background--The survivability model recommended for the ICDT methodology was developed by Honeywell during a study of flight control survivability through use of on-board digital computers (Reference 37). The acronym SUDIC was applied to this study and the analytical technique that was transformed into the survivability model was referred to as the Quick Analysis model.

The essence of design for affordable survivability is to be able to identify those system and subsystem configurations that are more survivable with negative or small penalties in the other "ilities." To make the best choices, it is important to be able to readily quantify the relative survivability of modifications of a basic system.

To accomplish this quantification, Honeywell has developed the software and model structure to analyze the survivability and reliability of a control-of-flight system. Its applicability is broad enough to consider control-of-flight equipment and other aircraft subsystems required to supply power or data to the flight control system (for example, hydraulic, electric, and air data). The model has the scope to show the effect on survivability of functional redundancy and the dispersion of components used to duplicate functions. At the same time, the problem definition requirements and quick computer turnaround minimize the resources required.

The initial motivation for developing this survivability analysis model was the approaching capability of digital fly-by-wire (DFBW) systems to identify damage to the FCS or surface actuation systems and to change control laws to enable the aircraft to fly without the affected components or surfaces.

Technology is developing for improved fault isolation within computers (References 36, 47-49), fault isolation in sensor sets using analytical

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[47] W.G. Bouricius, et al., "Reliability Modeling Techniques for Self-Repairing Computer Systems," Proc. ACM 1969 Annual Conference.

[48] J.H. Wensley, et al., "Design of a Fault Tolerant Airborne Digital Computer," NASA CR132252, October 1973 (SIFT-Standard Research Institute).

[49] R. Kayfes, et al., "Interpretive Computer Simulation for the Modular Spacecraft Computer," Logicon Report No. CSS-7254-R1410, November 1972.

redundancy (References 50-52), and actuator checking through input-output comparison. An additional level of redundancy (beyond the sensor count) has been demonstrated in simulation by reconstructing the signal of a failed gyro using other measurements and the analytical redundancy filter that is used originally to identify the sensor failure (Reference 53).

This growing capability in fault isolation, detection, and recovery of DFBW systems is opening a new dimension in the design of survivability aircraft; this is the idea of the reconfigurable control-of-flight systems.

3.5.4.8.2 Model Description--In the design stage the survivability analysis method using the Quick Analysis model generates quick estimates of the survivability of a particular configuration and its relation to the survivability of alternate configurations. The SUDIC study assumes that

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[50] J. Deckert, et al., "Reliable Dual-Redundant Sensor Failure Detection and Identification for the NASA F-8 DFBW Aircraft," C.S. Draper Lab Report R-1077, Cambridge, Maine, May 1977.

[51] T. Cunningham, et al., "Fault Tolerant Digital Flight Control with Analytical Redundancy," AFFDL-TR-77-25, May 1977 (Honeywell).

[52] T. Cunningham, and R. Poyneer, "Sensor Failure Detection Using Analytical Redundancy," JACC 1977, San Francisco, California, J ne 1977.

[53] T. Cunningham, J. Doyle, and D. Shaner, "State Reconstruction for Flight Control Reversion Modes," IEEE Control and Decision Conference, New Orleans, December 1977.

all capabilities for a reconfigurable system are in hand. The analysis method aids the designer in determining which capabilities to implement.

The six major steps in the survivability analysis are shown in Figure 29. They include all the features involved in a detailed survivability analysis. The procedure is kept efficient by using simple forms for much of the input data (Steps 1, 3) and by using independent computer programs for different parts of the problem. Once Steps 2 and 4 are completed, they need not be repeated in the process of looking at many practical variations of a system.

The combinations of damage events to components that are required to disable sections of a system are stated by writing Boolean algebraic statements (Step 5). The combinations of damaged sections that result in system kill are stated by writing more Boolean statements. In Step 6, the program PKILL combines all the algebraic statements, component vulnerable areas, the encounter history to compute kill probability of components of subsystems, and of the system. Furthermore, PKILL computes data useful to the designer in determining changes that will further enhance survivability.

Noteworthy aspects of this survivability analysis method are:

- The comparative simplicity of input data, and
- The program's conversion of Boolean statements of damage events (input) into probabilities of killing components, subsystems, and a system. (Boolean statements are better for showing the improvement from functional duplication or triplication than the single-hit probability models.)

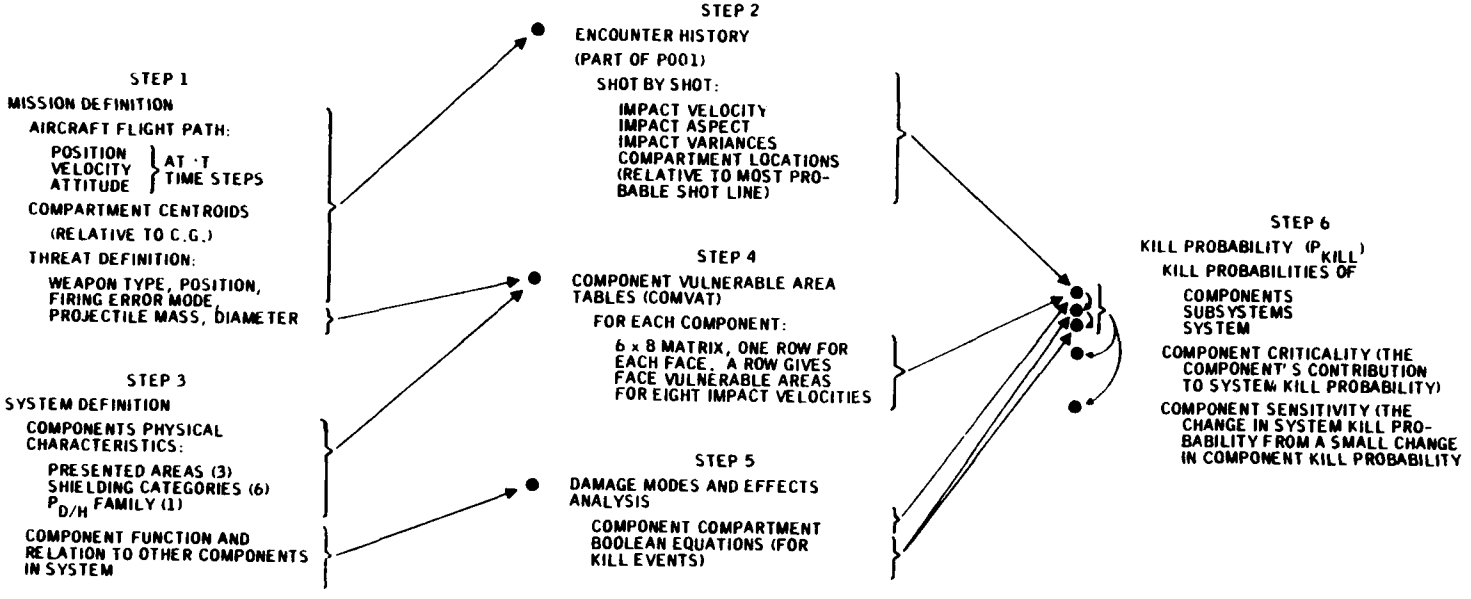


Figure 29. Six Major Steps in Survivability Analysis

Data preparation is kept simple primarily by having only a limited number of choices for component data. A component's susceptibility to damage is described by estimates of three areas (front, left face, and top) and seven integers. The first six integers designate a shielding category which represents an average shielding by other parts of the aircraft for each face of the component. (Currently four categories are used, but ten are permitted.) The seventh integer describes the component's intrinsic hardness by assigning it to a generic family of $P_{D/H}$ (probability of damage given a hit). Up to 15 families (generic component types) are used and each family has up to five $P_{D/H}$ curves (one for each of five projectile types).

During design, component locations in an aircraft are known only approximately. To simplify designation of component location, the aircraft is divided into seven compartments and components are simply assigned to the compartment that represents the appropriate part of the aircraft. A component's location is its compartment's centroid. To reduce the number of components considered, highly distributed systems may be assigned to the aircraft mass center (the eighth compartment). The criterion for choosing compartment boundaries is to provide resolution of the shot-by-shot hit probability distribution from the encounter history.

Thus, the complete physical description of each component, together with its shielding for each face, requires three face areas. These data, together with projectile mass, are used to compute a component vulnerable area for each face (Reference 37) of each component. An eighth integer assigns the component to a compartment.

Component kill probabilities are computed throughout a mission using the vulnerable area tables and the encounter history. The methods are straightforward and are described in detail in Reference 37. A significant feature is that the component kill probabilities are combined according to the Boolean rules established in the damage modes and effects analysis (Step 5) to yield subsystem and system kill probabilities. This is particularly important for two reasons.

First, component kill probability is a very pessimistic indicator of system kill probability whenever the component's function is duplicated by equipment which is located so as not be be killed by the same shot. Second, a single-hit-kill probability model is always optimistic when a component's function is duplicated because this model then predicts zero kill probability. A Boolean model system evaluates kill probability according to the degree of functional redundancy.

3.5.5 Illustrative Example--

3.5.5.1 Problem Modeling--This subsection illustrates the system effectiveness evaluation procedures using the state space system effectiveness model. The formulation used is directly applicable for simulation using the SESIP computer program. The basic problem was taken from Reference 15, Vol III, Example A. In the referenced document, treatment of the WSEIAC effectiveness formula, not including the survivability attribute, was illustrated. This subsection treats the same problem but uses the state space system effectiveness model. The survivability aspects of the example are described in separate subsections.

3.5.5.1.1 Problem--Determine the system effectiveness of an avionics system developed for a tactical fighter-bomber aircraft.

3.5.5.1.2 Mission Definition--At any time when an execution order is received, the aircraft shall take off immediately, receive a target assignment, proceed to target area, deliver weapon within 500 feet of target, and return to the operating base.

3.5.5.1.3 System Description--The system being considered consists of three major subsystems which are, where appropriate, subdivided into equipments.

Fire Control Subsystem	Doppler Navigator	Communication-Identification-Navigation
• Radar (search and terrain avoidence)	• Doppler navigator	• UHF direction finder
• Toss-bomb computer		• TACAN
• Sight system		• Instrument landing system
		• UHF transmitter-receiver
		• Identification equipment
		• Audio amplifier equipment

The equipments itemized are independent of each other, that is, the condition of any equipment does not influence the condition of any other.

3.5.5.1.4 Functions of Equipments--The fire control subsystem is employed in actual weapon delivery. It provides a radar display of the target and computation of weapon release point in the toss-bombing mode. It also provides, through the sight system, the aiming point for "lay-down" delivery. The terrain avoidance feature provides automatic control of the aircraft altitude.

The Doppler navigator provides the prime navigation function by computing and displaying information on both present position and distance/heading to target. Alternate navigation procedures are provided by the Tacan and the UHF direction finder. Each of these, however, requires ground station facilities.

The instrument landing system (ILS) provides the ability to land the aircraft under ceiling and visibility conditions which would otherwise prevent landing.

The UHF transmitter-receiver, the only radio-communications device, is employed for all in-flight radio communication. The audio amplifier equipment is employed with the UHF transmitter-receiver only and may be considered part of that equipment.

The identification equipment (IFF) provides a coded identification signal in response to an interrogation by friendly forces. Failure to provide the proper response can result in attack by friendly forces.

3.5.5.1.5 Functional Breakdown--The essential functions to be performed by the avionics system are listed below:

- Communication
- Identification
- Navigation
- Penetration
- Weapon delivery
- Landing

3.5.5.1.6 System Block Diagram--A general block diagram of the avionics system is shown in Figure 30.

3.5.5.1.7 Mission Profile--A time line representation of the mission being considered is shown in Figure 31. Three different modes of delivery are represented:

- Visual lay-down (VL)
- Visual toss (VT)
- Blind toss (BT)

Basic mission breakdown is as follows:

0.0 - 0.5 hours	Proceed to target area (communicate, navigate, identify)
0.5 - 0.6 hours	Identify target

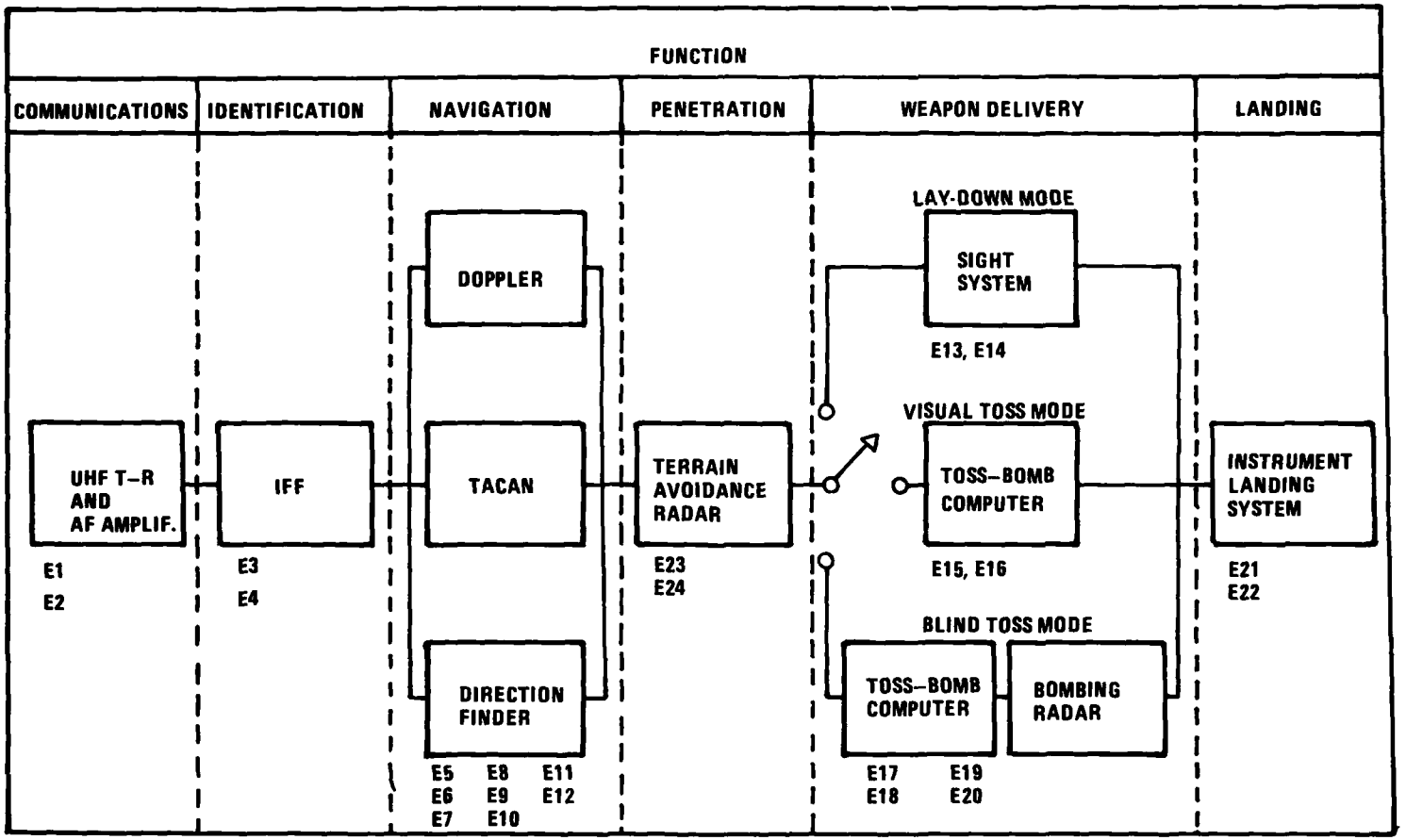


Figure 30. Avionics System: Functional Diagram

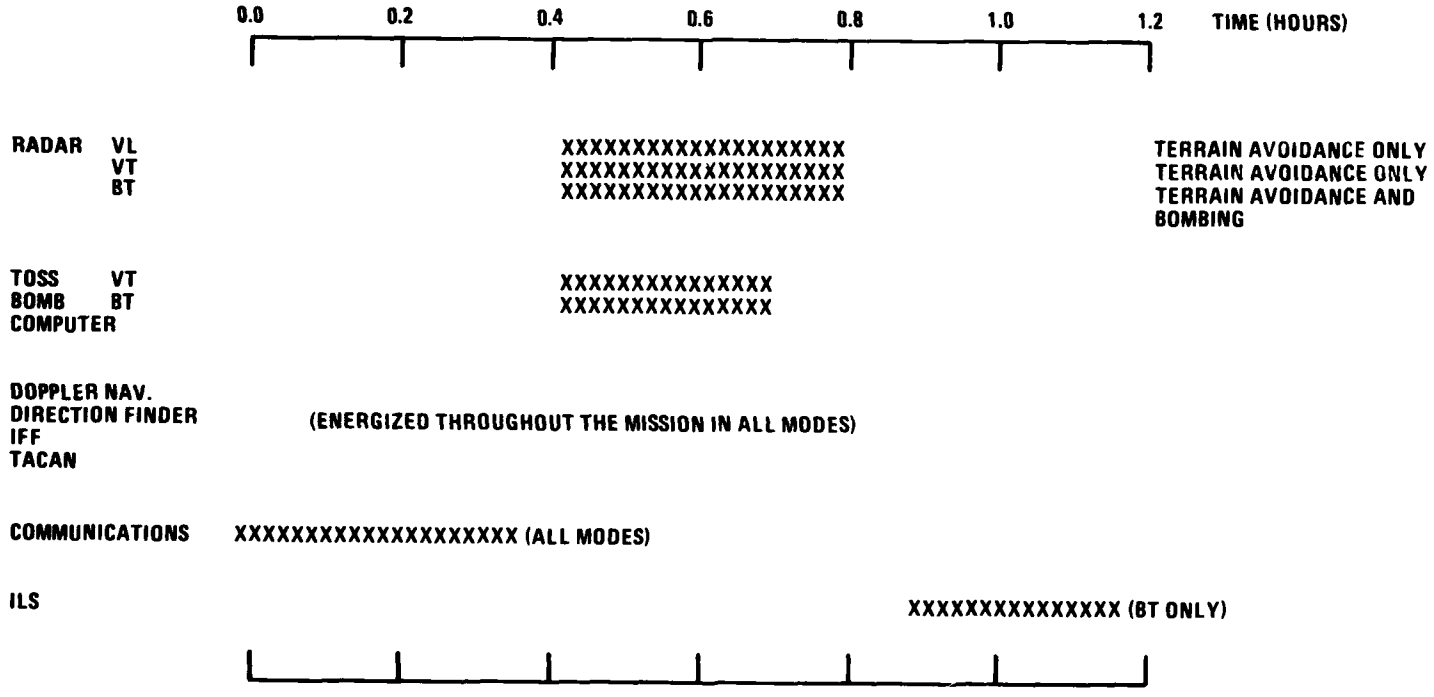


Figure 31. Mission Profile and Equipment Usage

0.6 - 0.65 hours	Deliver weapon
0.65 - 1.15	Return to assigned base (navigate, identify)
1.15 - 1.2	Land

3.5.5.1.8 Delineation of Mission Outcomes--

1. Mission is accomplished as stated in mission definition paragraph.
2. Mission is not accomplished as stated:

- Aircraft does not proceed without delay
  --One or more subsystems are in a state that prevents launching.
- Aircraft does not receive target assignment
  --Failure or inadequacy of one or more subsystems prevents receipt of target assignment
- Aircraft does not deliver weapon within 500 feet of target.
  --Aircraft does not reach target area
  Failure or inadequacy of one or more subsystems prevents reaching target area.
  --Aircraft does not identify target
  Failure or inadequacy of one or more subsystems prevents identification of target
  --Aircraft does not place weapon within 500 feet of target.
  Failure or inadequacy of one or more subsystems results in inaccurate delivery.

- Aircraft does not return to assigned operating base.
  --Aircraft lost
    Failure or inadequacy of one or more subsystems results in aircraft loss.
  --Aircraft returns to the wrong base.
    Failure or inadequacy of one or more subsystems prevents return to assigned base.

3.5.5.1.9 Specification of Figures of Merit--For the specific mission requirement, the major figure of merit is the probability that the mission, as defined, is accomplished.

Accomplishment of the mission depends upon the successful performance of several individual functions:

1. Takeoff
2. Receipt and acknowledgement of target assignment
3. Navigation to a point not more than five miles from target
4. Proper identification when interrogated
5. Penetration of enemy defenses
6. Identification of target and weapon delivery within 500 feet of target
7. Navigation to within 10 miles of assigned operating base.
8. Landing

3.5.5.1.10 System Model--The system model must express the probability of successfully completing a mission as a function of:

- The effectiveness of the system in each of the three delivery modes, and
- The probability of employing each delivery mode.

This can be represented by the following simple model:

$$E = \sum_{i=1}^{3} E_i P_i$$

where

E = system effectiveness

E_i = system effectiveness in mode i

P_i = probability of using mode i.

In the given problem we will be considering three different delivery modes. The values of P_i will be determined from consideration of tactical requirements and operational conditions. The values of E_i will be derived by combining the effectiveness figures for each mission function in accordance with the requirements for the stated mission mode.

3.5.5.1.11 Data Acquisition--Depending upon the design phase in which the system effectiveness evaluation is made, the sources of data will differ. During the definition phase, predictions will be based on failure and maintenance rates derived from previous projects. Later, when more

information becomes available from laboratory and field testing, the predicted failure and maintenance rates will be suitably updated.

3.5.5.1.12 Equipment Characteristics--Since the prime purpose of this example is to illustrate the effectiveness evaluation procedure, detailed derivations of failure rates and repair rates will not be given. The values which will be used in this example are listed in Table 27. These values were taken from Reference 15, Vol. III.

3.5.5.1.13 Determination of Availability--Equipment availability using the state space effectiveness model is determined in a straightforward manner employing the basic model. In present day work, availability is usually calculated as the steady state availability:

$$V = \frac{MTBF}{MTBF + MTTR}$$

where

V is the steady state availability or state readiness

MTBF is the mean time between failures

MTTR is the mean time between repairs

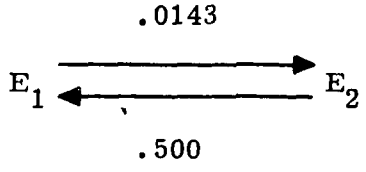
Many objections have been raised to this type of approach, such as the assumption of extremely long time periods available for making repairs, the assumption of allowing equipment to operate during the period between missions, etc.

TABLE 27. AVIONICS SYSTEM FAILURE AND REPAIR RATES

Equipment	Failure rate fr/hr	Repair rate rep/hr
Bombing radar	0.0312	0.167
Terrain avoidance radar	0.0250	0.125
Toss-bomb computer	0.0500	0.250
Sight system	0.0050	0.500
Doppler	0.0500	0.067
Direction finder	0.0100	0.500
Tacan	0.0200	0.250
Instrument landing system	0.0067	0.333
Communications equipment	0.0143	0.500
Identification equipment	0.0100	0.333

Using the state space effectiveness formulation, we have a number of alternatives available. We can extend the time required for maintenance and repair actions to any arbitrary length, simulating different mission turnaround times, or we can make it extremely long, thus approaching the steady state availability case. It is also possible to simulate a number of sequential missions with the proper turnaround time and thus obtain more accurate results.

Let us return now to our illustrative example. Referring to Figure 30, we will consider the first subsystem--communications. This subsystem consists of the UHF transmitter-receiver and the audio amplifier combination. Its failure rate (referring to Table 27) is 0.0143 fr/hr and the repair rate 0.500 rep/hr. The corresponding state diagram becomes:

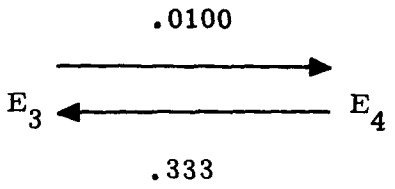


In this state diagram State 1 represents the operational communications subsystem, State 2 the unoperable status of the same subsystem. Initial conditions on States 1 and 2 are determined as follows:

1. If we are starting from the initial system point, equipment is operating and checked out at t = 0, then $P_1(0) = 1$, $P_2(0) = 0$.
2. If we are starting this time phase at some other point, say after the return from a particular mission, then the corresponding probabilities are determined by the values achieved at the end of that mission.

If we are interested only in the steady state availability figures, it will not make any difference how the initial conditions are selected provided they add up to unity.

The next subsystem under consideration is the IFF. Here again we find a single, independent equipment configuration. Its state diagram becomes:

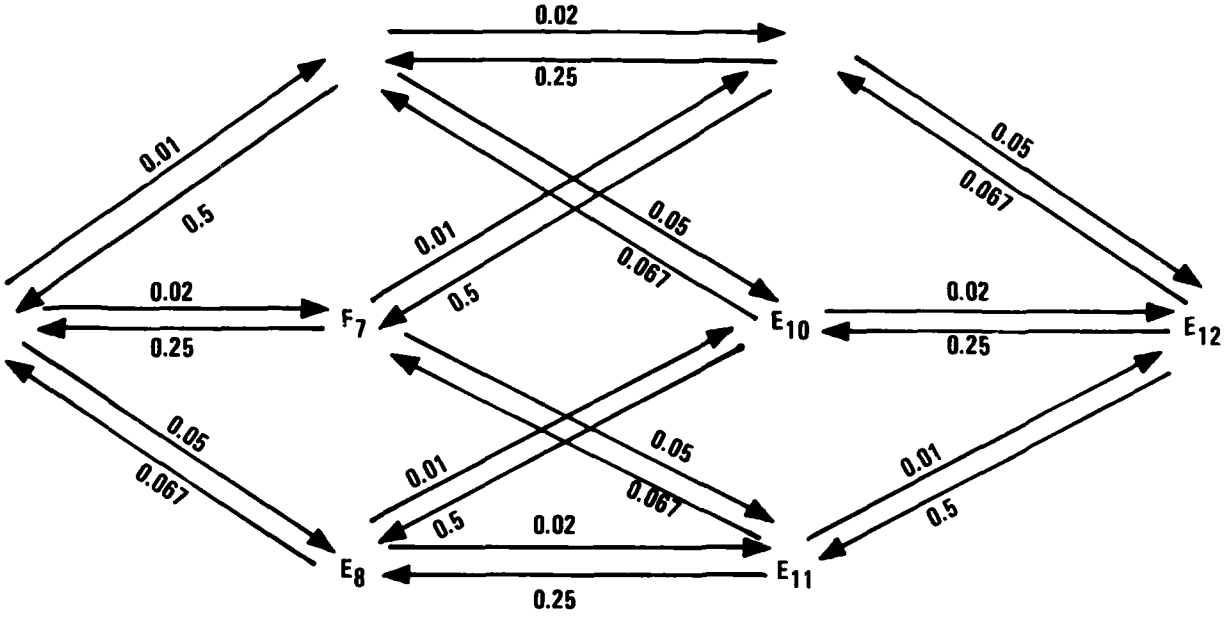


State 3 is the IFF operational state; State 4 is the IFF down state. Initial conditions again are determined in the same way as discussed earlier.

Our next subsystem, the navigation subsystem, consists of three navigational equipments essentially working in parallel. In this case we have three resulting equipment states for this system. The following nomenclature will be used:

State	Doppler	Tacan	Direction Finder
E_5	Operating	Operating	Operating
E_6	Operating	Operating	Down
E_7	Operating	Down	Operating
E_8	Down	Operating	Operating
E_9	Operating	Down	Down
E_{10}	Down	Operating	Down
E_{11}	Down	Down	Operating
E_{12}	Down	Down	Down

The resulting state diagram is shown below:

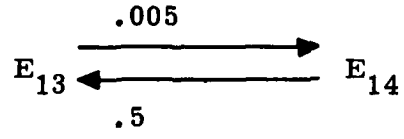


An alternate formulation would be to consider the three types of equipment making up the navigation subsystem to be independent, calculate their availabilities in the same manner as we did before in the case of communication and IFF subsystems, and then form the availability figures for the various states by using the probability product rule. This approach will result in three separate state diagrams each one having only two arrows, but we will have to form eight product terms.

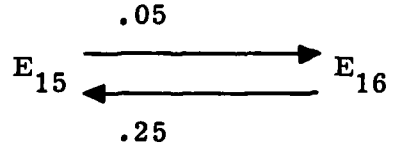
The bombing subsystem also consists of three parallel equipment combinations; however, the situation is this case is slightly different. In the blind toss bombing mode we will require only the bombing radar and toss-bomb computer; in visual toss mode we will require only the toss-bomb computer, and for lay-down delivery only the sight system. Here again

we have a choice in our representation of the existing requirements. Under the definitions stated above, it is clear that the sight system will be modelled separately, but how about the combination of bombing radar and toss-bomb computer? Here two alternatives are available. One is to consider the bombing radar and the toss-bomb computer separately; the other approach involves modeling the combined toss-bomb computer and bombing radar in a single state diagram and then setting up a separate state diagram for the toss-bomb computer alone. To gain some experience with the more complex state diagrams, we will select the last approach described above.

The state diagram for the sight system is:



For the visual toss bombing mode we can model the toss-bomb computer in a similar fashion:

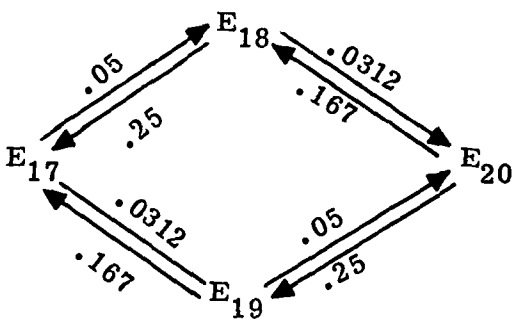


In the above state diagrams E_{13} and E_{15} represent the operating states and E_{14} and E_{16} the failed states.

For the blind toss mode our state diagram will have four distinct states designated as follows:

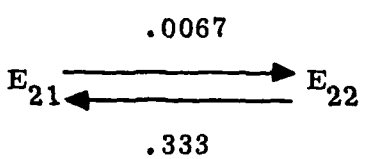
	Radar	Toss-bomb Computer
E_{17}	Operating	Operating
E_{18}	Operating	Down
E_{19}	Down	Operating
E_{20}	Down	Down

The corresponding state diagram takes the following form:

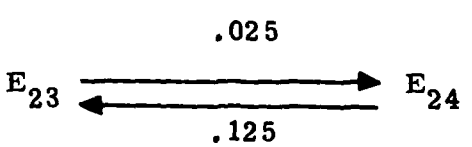


The instrument landing (ILS) and the terrain avoidance radar subsystems are single independent subsystems. Their state diagrams are:

ILS



Terrain avoidance radar



States 21 and 23 are operational states, 22 and 24 are failed states.

3.5.5.1.14 Probability of Launch--Under field operating conditions launch is not always ruled out just because a particular equipment is not ready. Since in many cases some bombing capability exists with even some inoperative equipment, the probability of launch in a degraded mode should be considered. Estimates for the probabilities of launch for the various equipment states are tabulated in Table 28.

3.5.5.1.15 Determination of Capability--There is only one more parameter to be determined for each functional equipment before we can proceed with the model exercise.

Communications Equipment: For the particular mission considered, the communications function is only required so that specific target assignment can be made or changed after the aircraft has taken off. For this example it will be further assumed that specific assignments will always be made while the aircraft is in flight. It is estimated that in 90 percent of the cases specific target assignments can be made before the aircraft is out of range. In the remaining 10 percent, an unsuccessful mission will result.

It is also estimated that environmental conditions and difficulties with ground equipment will prevent the required communication 5 percent of the time when the aircraft is within the operating range of the base station.

TABLE 28. PROBABILITIES OF LAUNCH

Equipment	State	Probability of Launch
Communications	1	1.0
	2	0.0
Identification (IFF)	3	1.0
	4	0.2
Navigation	5	1.0
	6	1.0
	7	1.0
	8	0.1
	9	0.8
	10	0.0
	11	0.0
	12	0.0
Lay-down delivery sight system	13	1.0
	14	0.8
Visual toss	15	1.0
Toss-bomb computer	16	0.7
Blind toss	17	1.0
Radar and computer	18	0.5
	19	0.0
	20	0.0
Instrument landing system	21	1.0
	22	0.95
Terrain avoidance radar	23	1.0
	24	0.0

The capability of the communications subsystem is expressed as the probability that the target designation and/or change is received and acknowledged by the aircraft.

Thus in operational state E_1

$$C_1 = (0.90)(0.95) = 0.855$$

In the disabled communications state the system capability is zero.

Identification Equipment (IFF): During the attack phase the aircraft is in the danger of being attacked, if it is not able to identify itself properly, and destroyed by friendly forces. The identification equipment in the operational state has a capability of unity. Destruction of the aircraft is not certain, however, even when the identification subsystem is in failed state. In this state the aircraft will survive if:

--It is not challenged, or

--It is challenged, but is not destroyed.

If we assume the probability of challenge being 0.90 and the probability of destruction 0.10, then

$$C_4 = (0.1) + (0.9)(0.9) = 0.91$$

Navigation Equipment: The aircraft must be able to navigate to within 5 miles of the target area by use of the navigation equipment; from this point target identification can be accomplished by other means. On the return flight it must be able to navigate to within 10 miles of its assigned base. While the navigation function can be supplied by three different equipments, the capability of each is different. The Doppler equipment

has a basic capability of 0.95, the Tacan of 0.9, and the direction finder (DF) of 0.8. However, because the Tacan and DF equipments require external signals from associated ground stations, the probabilities that these signals will be available must be considered. While the Doppler can be used at any time it is operating properly, the Tacan ground station will be available only 50 percent of the time and DF ground station only 40 percent of the time.

The actual capabilities for each equipment are:

$$C_{doppler} = 0.95$$

$$C_{tacan} = (0.9)(0.5) = 0.45$$

$$C_{df} = (0.8)(0.4) = 0.32$$

Next, we must consider the capabilities for the eight distinct states of the navigation subsystem. The capability of each state will be the capability of the operating equipment whose individual capability is the highest, if all equipments are equally available. In the case of the state in which both the Tacan and DF equipment are available, but the Doppler has failed (E_8), the probabilities that the ground stations for Tacan and DF will be available must also be considered. Assuming independence between the Tacan and DF ground stations, the capability in this state is:

C_8 = (Probability that Tacan can be used)(Tacan capability) +
(Probability that only DF can be used)(DF capability) =

$$= (0.5)(0.9) + (1.0 - 0.5)(0.4)(0.8) = 0.61$$

Target identification and weapon delivery equipment: The target can be identified either visually or by means of the radar equipment. The ability to deliver a weapon within 500 feet of an identified target is dependent upon the mode of the delivery. For the particular example these probabilities are estimated or based on previous experience.

Instrument landing equipment (ILS): The instrument landing system when functioning properly has a capability of 0.99. That is, a landing without damage to the aircraft or injury to the pilot can be made 99 times out of 100. In weather during which this equipment is not required, the probability of successful landing is 1.0.

If we assume that visual landing procedures are possible 95 percent of the time, the probability of successful landing if the ILS is operable is:

$$C_{21} = \text{(Probability of visual landing)(Probability of successful landing under visual conditions) + (Probability of ILS landing) (Probability of successful landing under ILS conditions)}$$
$$= (0.95)(1.0) + (0.05)(0.99)$$
$$= 0.9995$$

If the ILS is not operable, no capability under ILS conditions exist, and the overall landing capability is 0.95.

Terrain avoidance equipment: The terrain avoidance function of the radar is the only avionics equipment that contributes to the penetration ability of the aircraft. This equipment permits flying the aircraft at normal attack speeds at low altitudes, that is, below 1000 feet. Without this

equipment, such low level approaches are not possible. If we assume that the anticipated losses due to enemy action are 5 percent for low altitude approaches and 30 percent for high altitude approaches and that the atmospheric conditions which result in improper radar returns are anticipated 1 percent of the time, the penetration capabilities (the probability of penetrating enemy defenses), when the enemy action effectiveness is considered, are:

C_{23} = (Probability that radar permits low approach)(Probability of survival, given low approach) + (Probability radar does not permit low approach)(Probability of survival, given high approach)

= (0.99)(0.05) + (0.01)(0.70)

= .9475

C_{24} = Probability of survival, given high approach

= 0.70

A summary of the state capabilities is given in Table 29.

3.5.5.2 Model Exercise--In the previous subsections we have derived all the pertinent state diagrams for the individual subsystems. Our next task is to compute the subsystem availability numbers. Assume that for our example we elect to calculate the steady state availabilities. Then we can establish as the input to the SESIP eight independent state diagrams with their corresponding transition arrows (repair and failure rates). Assuming that we start with all equipment operational at time t = 0, initial conditions of unity are introduced in states 1, 3, 5, 13, 15, 17, 21, 23; initial conditions on all other states are equal to zero.

TABLE 29. STATE CAPABILITIES (SUMMARY)

Equipment	State	Capability
Communications	1	0.855
	2	0.000
Identification	3	1.000
	4	0.910
Navigation	5	0.950
	6	0.950
	7	0.950
	8	0.610
	9	0.950
	10	0.450
	11	0.320
	12	0.000
Lay-down delivery	13	0.900
Sight system	14	0.700
Visual toss	15	0.800
Toss-bomb computer	16	0.600
Blind toss	17	0.750
Radar and computer	18	0.400
	19	0.000
	20	0.000
Instrument landing system	21	0.9995
	22	0.950
Terrain avoidance radar	23	0.9475
	24	0.700

Next, we select the first time phase. In our example 1000 hour operation will be sufficient to establish the steady state conditions. At the end of 1000 hour, time increment probabilities associated with each state will be the desired availability figures. If we multiply these probabilities by the probabilities of launch (given in Table 28), the necessary initial conditions for the mission are established. In the next step we will remove all arrows associated with repair actions (there is no in-flight repair capability considered in this example) and those arrows associated with deenergized equipment during the first mission phase.

Examining the mission profile and equipment usage chart (Figure 31), we can select the necessary mission phases. In our example we select 0.4, 0.7, and 0.9 hours as intermediate points. At time t = 0 hours we deenergize terrain avoidance and bombing radar and the toss-bomb computer. At 0.4 hours we energize the terrain avoidance and bombing radar and the toss-bomb computer and deenergize the communications subsystem. At 0.7 hours we deenergize the toss-bomb computer; 0.1 hours later, at 0.8 hours we deenergize the terrain avoidance and bombing radar. At 0.9 hours the ILS subsystem is energized (This subsystem was deenergized at t = 0 hours). At 1.2 hours we stop our simulation.

At this point we have all the required probabilities associated with being in a given state at the end of the mission and now we can apply the proper capability coefficients (Table 29). Summing the products (state probability times state capability) for each state diagram, we can determine the subsystem effectiveness values.

3.5.5.2.1 Effectiveness for Individual Mission Types--The individual functional effectiveness figures may now be combined to evaluate the system effectiveness for each mission type. Using the conventional approach (assuming that subsystems are independent and that their effectivenesses can be combined using the product rule), we form product terms containing all those subsystem effectiveness numbers which are necessary for completing a specific mission.

In our example, communications, identification, navigation, landing, and penetration subsystems are common to all mission types. They differ only in the equipment necessary to complete a specific delivery. Thus we can combine states 1 - 12 and 21 - 24 in the common group and work with states 13-14 for lay-down delivery, 15-16 for visual toss mode, and 17-20 for blind toss mode.

Communication: The effectiveness attributes for the two communication states (E_1, E_2) are summarized as follows:

Availability (A) = [0.972 .0028]

Probability of Launch (U) $= \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$

Dependability $= \begin{bmatrix} .9943 & 0.0057 \\ 0 & 1.0 \end{bmatrix}$

$$\text{Capability (C)} = \begin{bmatrix} 0.855 \\ 0 \end{bmatrix}$$

Effectiveness of the communication subsystem is computed from the product

$$E = A \cdot U \cdot D \cdot C$$

$$E_C = 0.826323$$

Identification: The effectiveness attributes for the two IFF states (E_2, E_3) are summarized as follows:

$$A = [0.971 \quad 0.029]$$

$$U = \begin{bmatrix} 1.0 & 0 \\ 0 & 0.2 \end{bmatrix}$$

$$D = \begin{bmatrix} 0.9881 & 0.0119 \\ 0 & 1.0 \end{bmatrix}$$

$$C = \begin{bmatrix} 1.0 \\ 0.91 \end{bmatrix}$$

Effectiveness of the identification subsystem is computed from the product

$$E = A \cdot U \cdot D \cdot C$$

$$E_I = 0.975238$$

Navigation: The effectiveness attributes for the eight navigation states (E_5 - E_{12}) are summarized as follows:

$$A = [0.518,\ 0.011,\ 0.041,\ 0.001,\ 0.389,\ 0.031,\ 0.001]$$

$$U = \begin{bmatrix} 1.0 & & & & & & & \\ & 1.0 & & & & & & \\ & & 1.0 & & & & & \\ & & & 0.8 & & & & \\ & & & & 0.1 & & & \\ & & & & & 0.0 & & \\ & & & & & & 0.0 & \\ & & & & & & & 0.0 \end{bmatrix}$$

$$D = \begin{bmatrix} 0.9085 & 0.0109 & 0.0220 & 0.0561 & 0.0003 & 0.0007 & 0.0014 & 0.00 \\ 0. & 0.9195 & 0. & 0. & 0.0223 & 0.0568 & 0. & -0014 \\ 0. & 0. & 0.9306 & 0. & 0.0112 & 0. & 0.0575 & -0007 \\ 0. & 0. & 0. & 0.9418 & 0. & 0. & 0. & 0.0582 \\ 0. & 0. & 0. & 0. & 0.9647 & 0.0116 & 0.0234 & 0.0003 \\ 0. & 0. & 0. & 0. & 0. & 0.9763 & 0.9763 & 0.0237 \\ 0. & 0. & 0. & 0. & 0. & 0. & 0.9881 & 0.0019 \\ 0. & 0. & 0. & 0. & 0. & 0. & 0. & 1.0 \end{bmatrix}$$

$$C = \begin{bmatrix} 0.95 \\ 0.95 \\ 0.95 \\ 0.95 \\ 0.61 \\ 0.45 \\ 0.32 \\ 0.0 \end{bmatrix}$$

Effectiveness of the navigation subsystem is computed from the product

$$E = A \cdot U \cdot D \cdot C$$

$$E_n = 0.56278298$$

Penetration: The effectiveness attributes for the two penetration states, with or without the terrain avoidance radar, (E_{23}, E_{24}) are summarized as follows:

$$A = [0.833 \quad 0.167]$$

$$U = \begin{bmatrix} 1.0 & 0 \\ 0 & 0 \end{bmatrix}$$

$$D = \begin{bmatrix} .990 & .010 \\ 0.0 & 1.0 \end{bmatrix}$$

$$C = \begin{bmatrix} .9475 \\ 0.70 \end{bmatrix}$$

Effectiveness of the penetration subsystem is computed from the product

$$E = A \cdot U \cdot D \cdot C$$

$$E_p = 0.787206$$

Landing: The effectiveness attributes for the two landing states, with or without the instrument landing system, (E_{21}, E_{22}) are summarized as follows:

$$A = [0.980 \quad 0.020]$$

$$U = \begin{bmatrix} 1.0 & 0 \\ 0 & 0.95 \end{bmatrix}$$

$$D = \begin{bmatrix} 0.998 & 0.002 \\ 0 & 1.0 \end{bmatrix}$$

$$C = \begin{bmatrix} 0.9995 \\ 0.95 \end{bmatrix}$$

Effectiveness of the landing subsystem is computed from the product

$$E = A \cdot U \cdot D \cdot C$$

$$E_L = 0.981218$$

Lay-down mode (weapon delivery): The effectiveness attributes for the two states (E_{13}, E_{14}) of the sight subsystem used are summarized as follows:

$$A = [0.990 \quad 0.010]$$

$$U = \begin{bmatrix} 1.0 & 0 \\ 0 & 0.8 \end{bmatrix}$$

$$D = \begin{bmatrix} 0.999 & 0.001 \\ 0 & 1.0 \end{bmatrix}$$

$$C = \begin{bmatrix} .90 \\ .70 \end{bmatrix}$$

Effectiveness of the lay-down mode subsystem is computed from the product

$$E = A \cdot U \cdot D \cdot C$$

$$E_1 = 0.896402$$

Visual toss mode: The effectiveness attributes for the two states (E_{15}, E_{16}) of the toss bomb computer used are summarized as follows:

$$A = [0.833 \quad 0.167]$$

$$U = \begin{bmatrix} 1.0 & 0.0 \\ 0 & 0.7 \end{bmatrix}$$

$$D = \begin{bmatrix} 0.9851 & 0.0149 \\ 0 & 1.0 \end{bmatrix}$$

$$C = \begin{bmatrix} 0.80 \\ 0.60 \end{bmatrix}$$

Effectiveness of the visual toss mode subsystem is computed from the product

$$E = A \cdot U \cdot D \cdot C$$

$$E_v = 0.7340576$$

Blind toss mode: The effectiveness attributes for the four states (E_{17}-E_{20}) of the toss-bomb computer and bombing radar used for this function are summarized as follows:

$$A = [0.701 \quad 0.141 \quad 0.132 \quad 0.026]$$

$$U = \begin{bmatrix} 1.0 & & & \\ & 0.5 & & \\ & & 0 & \\ & & & 0 \end{bmatrix}$$

$$D = \begin{bmatrix} 0.0729 & 0.1047 & 0.0122 & 0.0002 \\ 0 & 0.9876 & 0 & 0.0124 \\ 0 & 0 & 0.9851 & 0.0149 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$C = \begin{bmatrix} 0.75 \\ 0.40 \\ 0.0 \\ 0.0 \end{bmatrix}$$

Effectiveness of the blind toss mode subsystem is computed from the product

$$E = A \cdot U \cdot D \cdot C$$

$$E_b = 0.543475$$

3.5.5.2.2 Overall System Effectiveness--A single, overall system effectiveness figure may be obtained from

$$E = E_{1d} P_{1d} + E_{vt} P_{vt} + E_{bt} P_{bt}$$

where the subscripts denote the type of mission,
E refers to mission effectiveness
P is the probability that a particular type mission will be flown.

P_{1d} (Probability of lay-down delivery) = (Probability of daytime mission) (Probability of good weather conditions)(Probability that lay-down delivery is preferred) = (.58)(.8)(.8) = .3712

P_{vt} (Probability of visual toss delivery) = (Probability of daytime mission) (Probability of good weather conditions)(Probability that toss bombing is preferred) = (.58)(.8)(.2) = 0.0928

P_{bt} (Probability of blind toss delivery) = (Probability of night mission) + (Probability of bad weather condition) - (Probability of night mission and bad weather conditions) = .42 + .2 - (.42)(.2) = .536

Substituting the mission effectiveness values in the above expression, we will obtain the overall expected mission effectiveness figure.

The individual functional effectiveness figures can now be combined to evaluate the system effectiveness in each of the modes of mission for lay-down mode, visual toss mode, and blind toss mode.

Lay-down delivery mode: (E_1)

$$E_{1d} = [E_C \times E_I \times E_N \times E_L \times E_p] \times E_l$$

$$= [(.826) \times (.975) \times (.553) \times (.991) \times (.787)] \times [.8964]$$

$$= [.347] \times [0.8964]$$

$$= 0.31$$

Visual toss mode:

$$E_{vt} = [E_C \times E_I \times E_N \times E_L \times E_p] \times E_v$$

$$= [0.347] \times [0.7340]$$

$$= .25$$

Blind toss mode:

$$E_{bt} = [E_C \times E_I \times E_N \times E_L \times E_p] \times E_b$$

$$= [0.347] \times [0.5435]$$

$$= .19$$

The single, overall system effectiveness is computed from:

$$E = E_{1d} P_{1d} + E_{vt} P_{vt} + E_{bt} P_{bt}$$

$$= 0.31 \times .3712 + 0.25 \times 0.0928 + 0.19 \times 0.536$$

$$= 0.115 + 0.023 + 0.102 = 0.24$$

3.5.5.3 Survivability Considerations--Including survivability in the effectiveness evaluation adds another matrix in the effectiveness calculation. For example, the effectiveness attributes for the eight navigation states would include availability (A), probability of launch (U), dependability (D), survivability (S), and capability (C). Effectiveness of the navigation subsystem is then computed from the product

$$E = A \cdot U \cdot D \cdot S \cdot C$$

where

$$\begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} & S_{17} & S_{18} \\ & S_{22} & S_{23} & S_{24} & S_{25} & S_{26} & S_{27} & S_{28} \\ & & S_{33} & S_{34} & S_{35} & S_{36} & S_{37} & S_{38} \\ & & & S_{44} & S_{45} & S_{46} & S_{47} & S_{48} \\ & & & & S_{55} & S_{56} & S_{57} & S_{58} \\ & & & & & S_{66} & S_{67} & S_{68} \\ & & & & & & S_{77} & S_{78} \\ & & & & & & & S_{88} \end{bmatrix}$$

The development of the S-matrix is given below. No quantitative values were available for this example. However, the product is straightforward and can be implemented in the SESIP program.

3.5.5.4 Survivability Analysis Example--Survivability is the capability to be shot up without being shot down. Survivability is designed into a system in several ways:

- Dispersing equipments that have the same or similar functions (so no shot takes out two or more)
- Replicating (and dispersing) equipments whose function is vital (Replication is done for dependability anyway.)
- Shielding equipment by placing it behind some relatively massive part of the airplane in relation to the direction of the major threat.

- Hardening equipment (expensive in terms of weight)
- Clustering essential (but small) components in one place so that they share vulnerable space

3.5.5.4.1 Survivability Analysis of Navigation States--Major subsystems (individual equipments are all independent) are listed with identifying acronyms of all equipment used for navigation functions.*

a.	Fire Control	
b.	Doppler Navigation	DOP
c.	Communication-Identification-Navigation (CIN)	
	UHF Direction Finder	UDF
	Tacan	TAC
	Instrument Landing System	ILS
	UHF Transmitter-Receiver	UTR
	Identification Equipment	ID
	Audio Amplifier	AUD

} 1

Notation

Boolean AND *

Boolean OR ⊕

*The functions performed by the equipments in subsystems b and c are designated by the acronyms.

Multiplication (usually of probabilities) •

Addition (usually of probabilities) +

S (DOP) $\triangleq$ survival probability of the DOP function

P (DOP) $\triangleq$ kill probability of the DOP function
ditto for all other functions

S = 1 - P (survival probability)

A superbar denotes NOT (NOT A = $\bar{A}$)

The P (equipment) is zero during a mission until one gets shot at. P grows with time during the shooting phase, so that S decreases with time during this phase. The first objective is to relate the S's of equipments to the S's of subsystem functions.

The functions performed by the equipments in subsystems b and c are:

Receive (requires both UTR and AUD)	RX	2
Identify self (requires both UTR and ID)	IFF	
Doppler navigation	NV1	
Tacan navigation (requires ground station and acceptably small range)	NV2	
Direction finder navigation (requires ground station and acceptably small range)	NV3	

Some auxillary variables

Tacan ground stations	GDT
Within Tacan range	RT

UDF ground station	GDD
Within UDF range	RD

Boolean statements for survival of subsystem functions, assuming individual equipments are dispersed, are:

$$RX = UTR * AUD \quad (3)$$

$$IFF = UTR * ID \quad (4)$$

$$NV1 = DOP \quad (5)$$

$$NV2 = TAC * GDT * RT \quad (6)$$

$$NV3 = UDF * GDD * RD \quad (7)$$

3.5.5.4.2 Navigation Functions and Navigation States--The three navigation functions have states of working or not working (1 or 0). The various combinations of states of navigation functions make up eight states of the navigations system. To evaluate survival probabilities of a navigation state, one must first evaluate survival probabilities of states of navigation functions.

How does equipment configuration affect states of navigation functions? Suppose TAC and UDF are packaged together so that a hit on their box takes out both equipment functions. Then the second and third navigation survival functions are:

$$NV2A = TACUDF * GDT * RT \quad (8)$$

$$NV3A = TACUDF * GDD * RD, \quad (9)$$

where the function $\overline{TACUDF}$ is what happens when the box gets hit. Throughout the shooting phase each box accumulates some kill probability. The events of killing the second navigations functions are

$$\overline{NV2} = \overline{TAC} \oplus \overline{GDT} \oplus \overline{RT} \tag{10}$$

and

$$\overline{NV2A} = \overline{TACUDF} \oplus \overline{GDT} + \overline{RT} \tag{11}$$

Since TACUDF is a bigger box than TAC, TACUDF has a higher kill probability;

$$P(TACUDF) = \text{Probability of } \overline{TACUDF} \tag{12}$$

and

$$P(TACUDF) > P(TAC) \tag{13}$$

The probability of losing the function NV2 is

$$P(NV2) = \text{Probability of NV2} \tag{14}$$

$$= P(TAC) + P(GDT) + P(RT) \tag{15}$$

$$- P(TAC)\,P(GDT) - P(TAC)\,P(RT) - P(GDT)\,P(RT)$$

$$+ P(TAC)\,P(GDT)\,P(RT)$$

Define

$$P(NV2A) = \text{Probability of } \overline{NV2A}$$

P(NV2A) is the same as (15) with P(NV2A) replacing P(NV2). The terms without products (first three) are the most important because probabilities are always less than 1 and products become small.

The same treatment applies for NV3 and NV3A.

Result: Common packaging will increase kill probability of individual equipment functions and reduce success probability of navigation functions.

3.5.5.4.3 Communications, Functions and States--UTR is required for both communications functions (3) and (4). Communication states are:

Receive and identify

Receive or identify

Neither

The receive and identify state's dependence on equipment functions is

$$RX * IFF = (UTR * AUD) * (UTR * ID) \quad (16)$$

$$= UTR * AUD * ID,$$

and the survival probability is

$$S(RX * IFF) = S(UTR) * S(AUD) * S(ID) \quad (17)$$

Now consider a second transceiver (UTRA) separated from the first one and operable for both RX and IFF functions. The receive and identify state's dependence on equipment functions now is

$$(RXA * IFFA) = (UTR + UTR) * AUD * ID \quad (18)$$

Now compare success probabilities of (17) and (18). Before the first shot hits, all boxes have S=1. Then

$$S(RX * IFF) = 1^3 = 1$$

and

$$\begin{aligned} S(RXA * IFF) &= S(UTR)\, S(AUD)\, S(ID) \\ &+ S(UTRA)\, S(AUD)\, S(ID) \\ &- S(UTRA)\, S(UTR)\, S(AUD)\, S(ID) \\ &= 2\,(1^3) - 1^4 = 1 \end{aligned} \tag{19}$$

The second transceiver does not contribute to survivability when there has been no threat to component survival.

Now assume we are into the shooting phase to the point where each box has a survival probability of 0.5. Then (17) and (18) are

$$S(RX * IFF) = (1/2)^3 = 1/8 \tag{20}$$

and

$$S(RXA * IFFA) = (1/2)^3 + (1/2)^3 - (1/2)^4 = 3/16$$

There is now a healthy increase (50 percent at this point in the mission) in success probability of the state receive and identify from duplicating the UTR function.

In the second communication state,

$$\begin{aligned} RX \oplus IFF &= UTR * AUD \oplus UTR * ID \\ &= UTR * (AUD + ID) \end{aligned} \tag{21}$$

The survival probability of the second communication state (receive or identify)

$$S(RX \oplus IFF) = S(UTR)\,S(AUD) + S(UTR)\,S(ID) - S(UTR)\,S(AUD)\,S(ID) \quad (22)$$

Also, adding the second transceiver

$$\begin{aligned} RXA \oplus IFFA &= (UTR \oplus UTRA) * AUD \\ &+ (UTR \oplus UTRA) * ID \\ &= (UTR \oplus UTRA) * (AUD \oplus ID) \\ &= UTR * (AUD \oplus ID) + UTRI * (AUD \oplus ID) \end{aligned} \quad (23)$$

and the survival probability for the state of receive or identify with the transceiver is

$$\begin{aligned} S(RXA \oplus IFFA) &= S(UTR)\,S(AUD) + S(UTR)\,S(ID) - S(UTR)\,S(AUD)\,S(ID) \\ &+ S(UTRA)\,S(AUD) + S(UTRA)\,S(ID) - S(UTRA)\,S(AUD)\,S(ID) \\ &- S(UTR)\,S(UTRA)\,S(AUD) - S(UTR)\,S(UTRA)\,S(ID) \\ &+ S(UTR)\,S(UTRA)\,S(AUD)\,S(ID) \end{aligned} \quad (24)$$

When all S's are 1, (22) and (24) are both 1. But when all S's are 1/2, (22) is

$$S(RX \oplus IFF) = 2(1/4) - (1/3) = 3/8 \quad (25)$$

and (24) is

$$S(RXA \oplus IFF) = 4(1/4) - 4(1/8) + 1/16 = 7/16$$

After the probability of success of every individual box is reduced to 1/2, the success probability of the state receive or identify is 16 percent higher if the UTR box is duplicated. Note also that the state receive or identify has much higher survival probability than the state receive and identify at the same stage in the mission (compare (25) with (20)).

3.5.5.4.4 Navigation States--Navigation states are eight combinations of the three navigation functions working and not working. Since the functions are independent, state probabilities are products of function probabilities. For example, the survival probability for navigation state N_1 is

$$S(N_1) = S(DOP)\, S(NV2)\, S(NV3)$$

Before proceeding, shorten notation by defining

$$S_1 \triangleq S(DOP)$$

$$S_2 \triangleq S(NV2)$$

$$S_3 \triangleq S(NV3)$$

3.5.5.4.5 Function States and Probabilities--We assume no repair capability, so that any function in its 0 state remains there with probability 1. Any function working at the beginning of a threat encounter is accumulating kill probability (in a software analysis of the encounter), so

P_i is monotone nondecreasing (and usually increasing)

(P_i starts at 0)

Therefore

S_i *is monotone nonincreasing (and usually decreasing)*

S_i starts at 1 since $S_i = 1-P_i$

Without repair capability, a function cannot make a transition from its 0 state to its 1 state.

As an example, consider transitions between states N_1 and N_2.

	DOP	*TAC*	*DF*
N_1	1	1	1
N_2	1	1	0

Denote elements of the survivability matrix by S_{ij}.

The elements that relate states N_1 and N_2 are:

$S_{11} = S_1 S_2 S_3$ = probability of all three navigation functions surviving

$S_{22} = S_1 S_2 1$ = probability of functions 1 and 2 surviving and function 3 remaining in 0 state

$S_{12} = S_1 S_2 (1-S_3)$ probability of functions 1 and 2 surviving and
$= S_1 S_2 P_3$ function 3 not surviving

$S_{21} = S_1 S_2 0=0$ because DF cannot repair itself

Inspection of the navigation state table then shows that

$$S_{ij} = 0, \; i > j \qquad\qquad i, j$$

because 0 to 1 transitions would occur. There are some terms above the matrix diagonal that are 0 for the same reason.

The remaining diagonal terms are:

$$S_{33} = S_1 S_3$$

$$S_{44} = S_1$$

$$S_{55} = S_2 S_3$$

$$S_{66} = S_2$$

$$S_{77} = S_3$$

$$S_{88} = 1$$

Transitions by degraded performance due to damage have the probabilities:

$N_1 \rightarrow N_2 \qquad S_{12} = S_1 S_2 (1-S_3) = S_1 S_2 P_3$

$N_1 \rightarrow N_3 \qquad S_{13} = S_1 (1-S_2) S_3 = S_1 P_2 S_3$

$N_1 \rightarrow N_4 \qquad S_{14} = S_1 (1-S_2) (1-S_3) = S_1 P_2 P_3$

$N_1 \rightarrow N_5 \qquad S_{15} = (1-S_1) S_2 S_3 = P_1 S_2 S_3$

$N_1 \rightarrow N_6 \qquad S_{16} = (1-S_1) S_2 (1-S_3) = P_1 S_2 P_3$

$N_1 \rightarrow N_7 \qquad S_{17} = (1-S_1) (1-S_2) S^3 = P_1 P_2 S_3$

$N_1 \rightarrow N_8 \qquad S_{18} = (1-S_1) (1-S_2) (1-S_3) = P_1 P_2 P_3$

$N_2 \rightarrow N_3$ $\quad S_{23} = 0$ (requires repair of DF state)

$N_2 \rightarrow N_4$ $\quad S_{24} = S_1 (1-S_2) = S_1 P_2$

$N_2 \rightarrow N_5$ $\quad S_{25} \quad 0$ (requires repair of DF state)

$N_2 \rightarrow N_6$ $\quad S_{26} = (1-S_1) S_2 = P_1 S_2$

$N_2 \rightarrow N_7$ $\quad S_{27} = 0$ (requires repair of DF state)

$N_2 \rightarrow N_8$ $\quad S_{28} = (1-S_1)(1-S_2) = P_1 P_2$

$N_3 \rightarrow N_4$ $\quad S_{34} = S_1 (1-S_3) = S_1 P_3$

$N_3 \rightarrow N_5$ $\quad S_{35} = 0$ (requires repair of Tacan state)

$N_3 \rightarrow N_6$ $\quad S_{36} = 0$ (requires repair of Tacan state)

$N_3 \rightarrow N_7$ $\quad S_{37} = (1-S_1) S_3 = P_1 S_3$

$N_3 \rightarrow N_8$ $\quad S_{38} = (1-S_1)(1-S_3) = P_1 P_3$

$N_4 \rightarrow N_5$ $\quad S_{45} = 0$ (requires repair of Tacan state)

$N_4 \rightarrow N_6$ $\quad S_{46} = 0$ (requires repair of Tacan state)

$N_4 \rightarrow N_7$ $\quad S_{47} = 0$ (requires repair of DF state)

$N_4 \rightarrow N_8$ $\quad S_{48} = (1-S_1) = P_1$

$N_5 \rightarrow N_6$ $\quad S_{56} = S_2 (1-S_3) = S_2 P_3$

$N_5 \rightarrow N_7$ $\quad S_{57} = (1-S_2) S_3 = P_2 S_3$

$N_5 \rightarrow N_8$ $\quad S_{58} = (1-S_2)(1-S_3) = P_2 P_3$

$N_6 \rightarrow N_7$ $\quad S_{67} = 0$ (requires repair of DF state)

$N_6 \rightarrow N_8$ $\quad S_{68} = 1-S_2 = P_2$

$N_7 \rightarrow N_8$ $\quad S_{78} = 1-S_3 = P_3$

The survivability matrix for the eight navigation states is now seen to have the form:

$$\begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} & S_{17} & S_{18} \\ & S_{22} & 0 & S_{24} & 0 & S_{26} & 0 & S_{28} \\ & & S_{33} & S_{34} & 0 & 0 & S_{37} & S_{38} \\ & & & S_{44} & 0 & 0 & 0 & S_{48} \\ & & & & S_{55} & S_{56} & S_{57} & S_{58} \\ & & & & & S_{66} & 0 & S_{68} \\ & & & & & & S_{77} & S_{78} \\ & & & & & & & 1 \end{bmatrix}$$

The significant fact about the form of the survivability matrix is that two thirds of its elements above the diagonal are non zero. The values of the non-zero entries will depend strongly on the intensity of the threat encountered.

3.6 SYSTEM SELECTION/OPTIMIZATION PROCESS

3.6.1. Background

In the event that more than one control-of-flight system candidates equal or exceed the effectiveness goal for the mission(s) and stay within the cost

constraints for the system, a selection process is required to determine an optimal system. This optimal system selection must be based on criteria involving some combination of effectiveness and cost measures. This criterion is referred to as a measure of worth or a utility measure.

The technique used to perform this selection/optimization step of the ICDT design methodology requires an application of linear programming. Usually linear programming problems are solved by a recursive method called the Simplex method. Honeywell has a modified Simplex program called ALPS which stands for advanced linear programming system and it has the practical capability of solving problems that have up to 850 constraints. Almost any computerized Simplex method, however, will handle enough constraints to solve the ICDT system selection/optimization problem.

In essence this linear programming technique is used to determine values of the designer/customer selected utility measure for each system candidate that has passed the defined thresholds established for cost and effectiveness. The utility criteria should be selected during the problem definition, step 1, along with the threshold constraints on cost and effectiveness. For the ICDT problem, utility measures such as the minimized cost for a constrained value of effectiveness or the maximized effectiveness for a constrained value of cost might be appropriate.

To illustrate the application of the selection/optimization process, an example is presented that shows how the optimized selection can be affected by the choice of the utility measures (or measure of worth) to be optimized. This problem involves the selection of a mix of candidate solutions to meet a set of effectiveness measures rather than the selection of only one system. The principles of the selection process are the same for either case, however, and are well illustrated in this example.

3.6.2 Illustrative Example

Six rather standard measure of worth models are described below. These models are useful for problems in which an optimal mix of systems is to be found to satisfy specific objectives.

Measure I: Minimize cost ($Z = \bar{C}^T . \bar{X}$) subject to minimum and maximum performance vector constraint ($\bar{b} \leq P \leq \bar{a}$)

Measure II: Maximize overall mix performance ($Z = \sum_{j=1}^{M} P_j$) subject to a mix cost constraint and minimum and maximum performance constraints ($\bar{b} \leq \bar{P} \leq \bar{a}$ and $\bar{C}^T \bar{X} \leq K$)

Measure III: Maximize relevant normalized performance ($Z = \bar{R}^T \bar{P}^1$), where $\bar{P}^1$ represents the performance vector normalized by division of each component by its maximum value, subject to cost, minimum performance, and maximum performance constraints ($\bar{c}^T x \bar{C}$, $\bar{b} \leq \bar{P} \leq \bar{a}$)

Measure IV: Minimize cost ($Z = \bar{c}^T\bar{x}$) subject to minimum and maximum performance accomplishment ($\bar{b} \leq \bar{P} \leq \bar{a}$) and also minimum relevant normalized performance ($\bar{R}^T\bar{P}^1 \leq \bar{d}$)

Measure V: Maximize the multipurpose performance capability ($Z = \bar{E}^T\bar{X}$) subject to the usual cost, minimum, and maximum performance capability constraints. The vector $\bar{E}$ has components $E_i = \frac{1}{M}\sum_{i=j}^{M} e_{ij}$ $i=1,2,---$, N which represents the average unit of effectiveness of the i^{th} avionics system Ai.

Measure VI: Maximize the relevant multipurpose performance capability ($Z = \bar{E}_R{}^T\bar{X}$) subject to cost, minimum and maximum performance constraints ($\bar{e}^T\bar{x} \leq C$, $\bar{b} \leq \bar{P} \leq a$) where the vector $\bar{E}_R$ represents the average weighted unit effectiveness with the weights set to the ratio of priority to maximum performance level (Rj/P_{jMAX}); $j=1, 2, ---, M$.

The symbolic notation used above is defined as follows:

Z = the objective functional (linear)

$C = \bar{C}^T \cdot \bar{X} = \sum_{i=1}^{N}\sum_{j=1}^{M} C_i x_{ij}$ = total mix cost

N = number of system candidates

M = specific objectives of mission

X_{ij} = number of systems A_i allocated toward accomplishment of the j^{th} specific objective

X = the allocation mix, an N x M matrix array

$$X_{11}, \; X_{12} \; - \; - \; X_{ij} \; - \; - \; X_{1M}$$

$$X_{i1}, \; X_{i2} \; - \; - \; X_{ij} \; - \; - \; X_{iM}$$

$$X_{N1}, \; X_{N2} \; - \; - \; X_{Nj} \; - \; - \; X_{NM}$$

C_i = unit cost of the i^{th} system A_i

P_j = performance of the j^{th} objective

R_j = priority ranking of the j^{th} objective

a = component of a constraint vector $\bar{a}$

b = component of a constraint vector $\bar{b}$

e_{ij} = unit effectiveness of i^{th} systems against j^{th} objective.

SECTION 4

ICDT DEMONSTRATION PROGRAM

The general procedure for designing the non-data processing system was described in Section 3.4.2. To show that ICDT methodology is a viable approach and that it works, a demonstration program was developed focussing attention on the integrated sensor system design which is an important subset of the overall ICDT process. The result of this effort is an interactive program capable of generating candidate sensor sets and a means of evaluating the performance of the sensor sets. The interactive program is operational on Honeywell and ASD computers. It has been successfully used to demonstrate the design of integrated sensor sets. The purpose of this section is to describe and document the ICDT demonstration program. The problem of determining integrated sensor sets to meet the mission requirements is described first. The integrated sensor set design procedure and the data bases required for implementing it are described next. This is followed by a discussion of performance evaluation of integrated sensor sets. Implementation of the demonstration program on the interactive computer is described next. Finally an example is given to illustrate the design of integrated sensor sets.

4.1 PROBLEM DEFINITION

The design problem is to seek a specification of the sensor system which will meet the mission requirements and to determine how it will be placed and connected to the avionic data processing hardware. The designer decides on a particular aircraft, the specific missions the aircraft will have to perform, how well they should be accomplished, and what the probability of survival of the aircraft itself should be in accomplishing the missions. In addition, he may also impose restrictions on the sensor systems available to meet the above requirements. These restrictions might be in the form of quantitative limits on cost, volume and/or weight of the total sensor system or they might be a matter of simply minimizing all of the above.

The specific mission considered in this study is the air-to-ground delivery of conventional bombs and consists of the following mission segments:

- Take off
- Climb
- Cruise
- Detect/Acquire target
- Deliver weapon

The COF system provides, in general, the flight control, navigation, weapon delivery and effectiveness management functions. Integration of sensors is achieved by combining the measurement requirements of the above COF functions.

4.2 INTEGRATED SENSOR SET DESIGN PROCEDURE

The problem of designing a sensor candidate set can be divided into two parts: generation of sensor candidate sets and evaluation against the mission performance requirements. The brute force approach, in which all possible combinations of sensors are considered, leads to a large number of candidate sets making them very costly to evaluate. The following design procedure generates a few candidate sensor sets based on the eventual performance of the integrated COF system.

In the following, a design procedure based on the five classical steps of the ICDT methodology is presented for the integrated sensor set design problem. The procedure is described in terms of the user/computer interaction, mission data base, sensor data base, sensor set generation, and performance analysis. A block diagram showing the five steps in the design procedure and the interface with the mission and sensor data bases is given in Figure 32.

Step 1 of the design process is mission specification. In this step the user specifies the required mission parameters with the help of the mission data base. The mission parameters include the control-of-flight (COF) functions needed for the mission, the mission trajectory parameters, the sensor requirements, the weapon characteristics, and the required target probability of kill. In step 2 of the design process, projected measurement requirements for the various COF functions are integrated to form projected measurement requirements for the mission. Candidate sensor sets are generated in step 3 to satisfy the projected measurement requirements by using the sensors in the sensor data base. In step 4, the navigation and

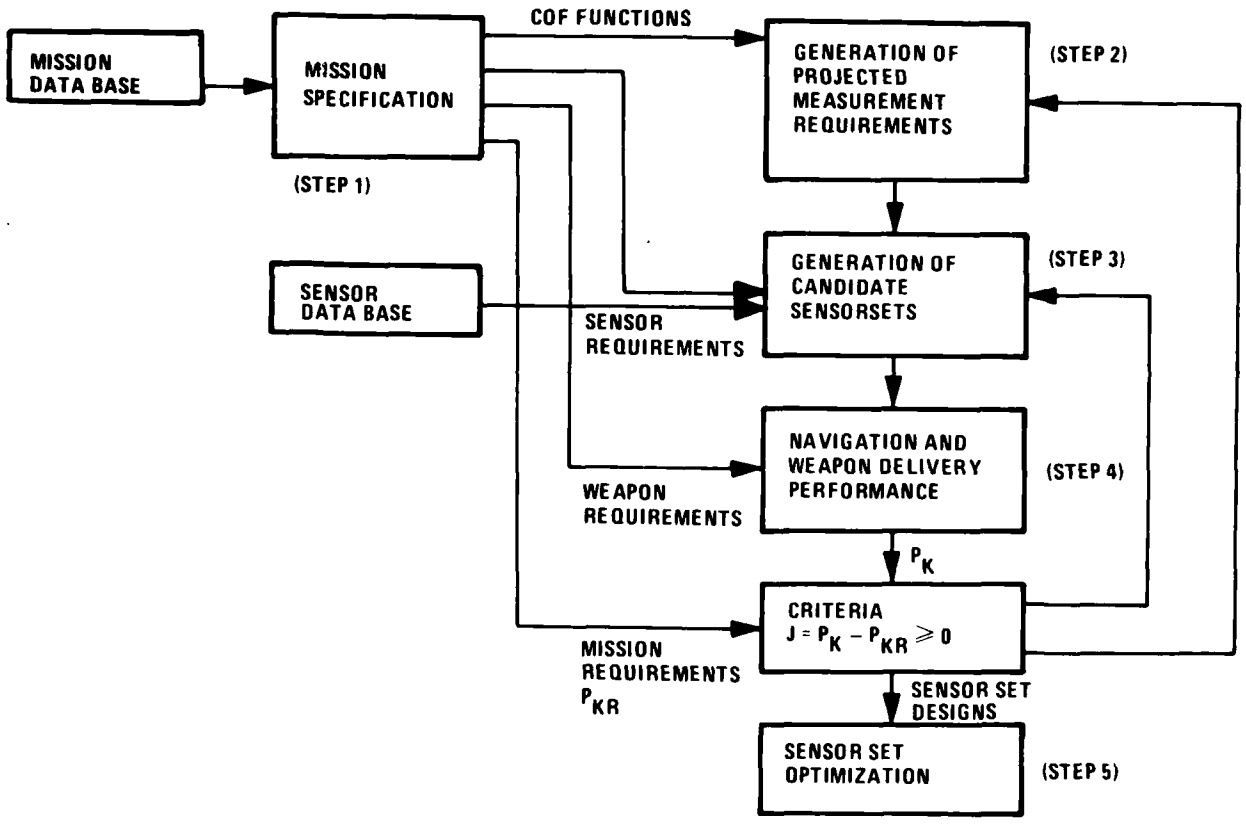


Figure 32. Integrated Sensor Set Design Process

weapon delivery performance is evaluated for the candidate sensor sets to check if the required performance is obtained. The final optimization of the sensor set design is made by the designer in step 5 to trade off performance against cost, weight, and other sensor set characteristics. These steps in the design process are described in detail in the following sections.

4.2.1 Mission Specification and Mission Data Base

The designer/computer interaction is provided to specify the mission performance, to select aircraft, weapon, and target, and to modify the mission and aircraft parameters defined in the mission data base. Also interaction is provided to modify the sensor selection criteria and the sensor set physical restrictions (for example, total cost, total weight, etc.).

The mission data base consists of a library of aircrafts, weapons, and targets that are presented in the form of menu for selection by the designer. It also contains typical accuracy and reliability requirements for the measurements needed by the COF functions. As mentioned before, only one specific mission, namely, air-to-ground delivery of conventional bombs is considered in the demonstration program. The mission performance is the target probability of kill for single shot bomb delivery.

Even though three different aircrafts, F-111, B-52, and F-16, are selectable from the mission data base, the aircraft dynamics is not utilized and the flight control is assumed to be perfect. Various targets and weapons are available in the mission data base. The mean area of effectiveness

for the targets and weapons for two different impact angles is shown in Table 30. This information is used by the weapon delivery performance program to compute the target probability of kill. The specific mission trajectory (see Figure 33) is generated by the trajectory generator program developed by Honeywell (See Reference 28). The mission trajectory parameters, namely, range to target, cruise altitude, cruise speed and weapon release altitude, can be specified to modify the mission trajectory.

The sensor selection criterion consists of weighted combinations of cost, weight, volume, and power. This criterion is used to eliminate sensor sets which are neither better in quality nor in selection value than the baseline sensor set. Also it is used to order the list of candidate sensor sets for presentation. Various sensor set restrictions, namely, total cost, total weight, total volume, and total power, can be specified. These are soft restrictions in that a candidate sensor set is not eliminated because it does not meet these restrictions. The restrictions satisfied are indicated in the list of candidate sensor sets presented to the designer.

4.2.2 Integrated Measurement Requirements and Sensor Data Base

Sensor integration is achieved by combining the measurement requirements of the COF functions. The measurement requirements are specified for accuracy and reliability. For the demonstration program the measurement requirements for flight control, navigation, and weapon delivery functions are assumed. Typical values for these requirements are shown in Tables 31 and 32 for accuracy and reliability respectively. These are modified by the program if the mission specification is changed by the user. In addition, the user can specify which control-of-flight functions are to be

TABLE 30. MEAN AREA OF EFFECTIVENESS OF WEAPON TARGET COMBINATIONS

WEAPONS	IMPACT ANGLE	TARGETS					
		ANTI-AIRCRAFT GUN	TRUCK	ROCKET LAUNCHER	ARTILLERY	ARMOURED PERSONNEL CARNER	GROUND TO GROUND ROCKET
Mk 81	30°	2300	3100	1090	2610	837	19000
	75°	5500	4350	1460	6350	1370	43000
Mk 82	30°	4060	4290	1790	4560	1300	30500
	75°	8970	7190	2640	10400	2180	60000
M 117	30°	4940	8300	2790	5520	1670	36700
	75°	11400	10400	3850	12900	2730	76000
Mk 83	30°	6820	8400	3360	7830	2090	48000
	75°	17400	12700	5430	20400	5000	103000
Mk 84	30°	9000	12500	5380	10800	3130	60500
	75°	24200	17000	8250	27600	6040	142000
AGM-12B	30°	3170	3750	1760	3180	904	25000
	75°	2170	3300	1010	2550	768	14000
AGM-12C	30°	6660	7360	3000	7100	2000	46900
	75°	5590	7900	3600	9000	2370	28000

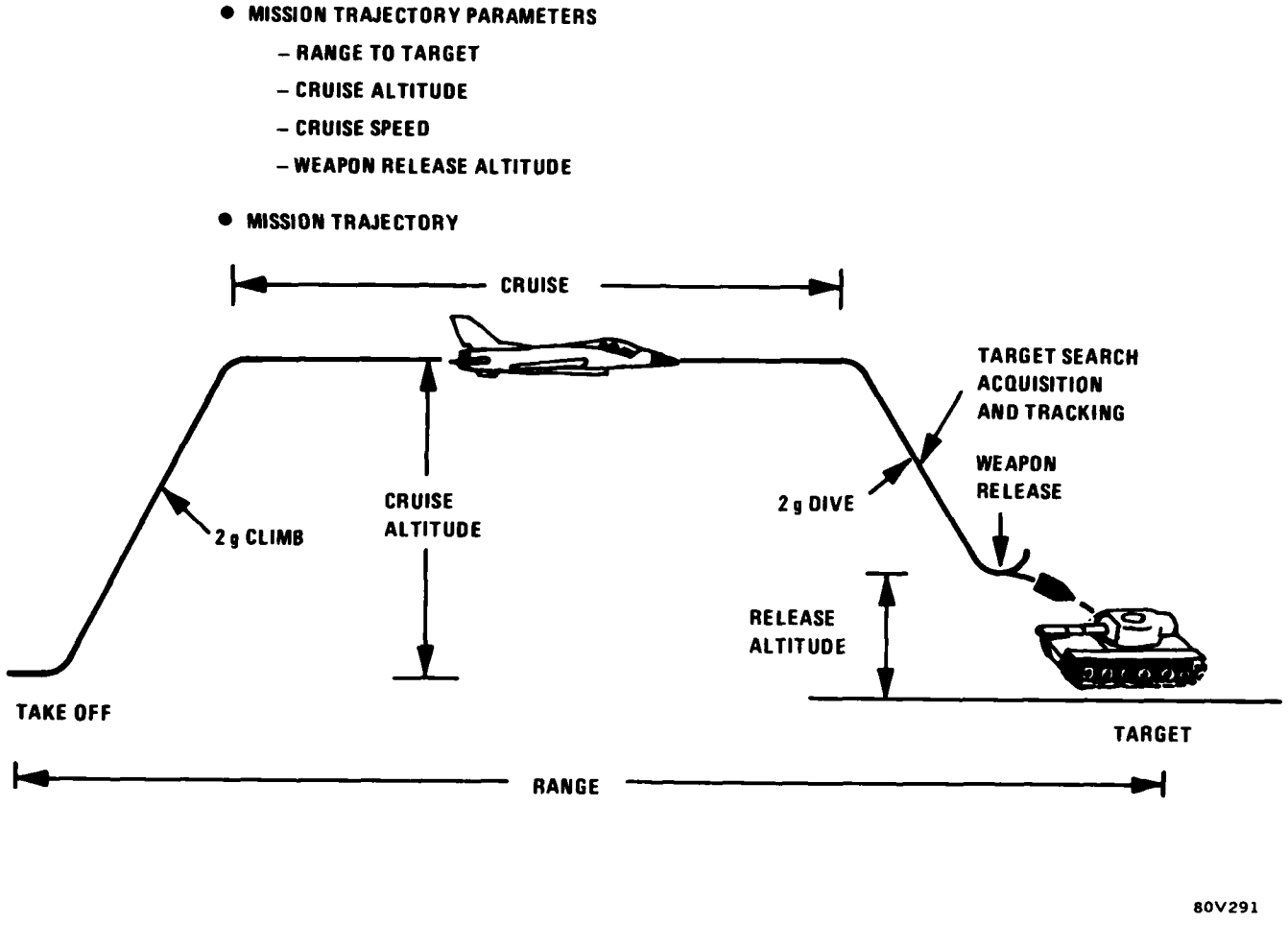


Figure 33. Specific Mission Trajectory used for the ICDT Demonstration Program

TABLE 31. MEASUREMENT REQUIREMENTS FOR ACCURACY

No.	Measurement	Flight Control	Navigation	Weapon Delivery	Integrated
1	Airspeed (knots)	15.0000	-	15.0000	15.0000
2	Altitude (feet)	50.0000	-	50.0000	50.0000
3	Azimuth (mrad)	-	-	1.7000	1.7000
4	Elevation (mrad)	-	-	3.2000	3.2000
5	Range (feet)	-	-	16.0000	16.0000
6	Roll rate (deg/hr)	.1600	.0800	-	.0800
7	Pitch rate (deg/hr)	.1600	.0800	-	.0800
8	Yaw rate (deg/hr)	.1600	.0800	-	.0800
9	Long accn (mg)	.0340	.0170	-	.0170
10	Late accn (mg)	.0340	.0170	-	.0170
11	Vert accn (mg)	.0340	.0170	-	.0170

TABLE 32. MEASUREMENT REQUIREMENTS FOR RELIABILITY

No.	Measurement	Flight Control	Navigation	Weapon Delivery	Integrated
1	Airspeed (knots)	.9800	-	.9500	.9800
2	Altitude (feet)	.9800	-	.9500	.9800
3	Azimuth (mrad)	-	-	.9900	.9900
4	Elevation (mrad)	-	-	.9900	.9900
5	Range (feet)	-	-	.9900	.9900
6	Roll rate (deg/hr)	.9980	.9000	-	.9980
7	Pitch rate (deg/hr)	.9980	.9000	-	.9980
8	Yaw rate (deg/hr)	.9980	.9000	-	.9980
9	Long accn (mg)	.9900	.9000	-	.9900
10	Late accn (mg)	.9900	.9000	-	.9900
11	Vert accn (mg)	.9900	.9000	-	.9900

integrated and the program combines the individual requirements to get integrated measurement requirements. These are also shown in Tables 31 and 32. Finally, the user can modify these integrated measurement requirements before generating candidate sensor sets.

The simple sensor data base developed for this demonstration program is defined in the following. Four types of sensors are chosen to be included in the sensor data base. These are body rate sensors, body acceleration sensors, airdata sensors, and target acquisition and tracking sensors.

The sensor data base contains sensors manufactured by different companies. The accuracy data for the measured variables for each sensor in the data base are shown in Table 33. The reliability of these measurements is calculated from the mission duration and the mean time between failure (MTBF) data for the sensors. In addition to this MTBF data, the cost, weight, volume, and power requirement data for the sensors are shown in Table 34.

4.2.3 Generation of Candidate Sensor Sets

The problem of generating sensor candidate sets, for the purpose of evaluating them for sensor integration, is an important one. The brute force approach, in which all possible combinations of sensors are considered, leads to a very large number of candidate sets making them almost impossible to evaluate. Consider, for example, a control-of-flight system which needs N independent sensor measurements. If the sensor data base contains 10 different sensors for each of these measurements, then the number of possible sensor combinations is given by 10^N. Thus the need exists for a

TABLE 33. SENSOR MEASUREMENT ACCURACY DATA

No	Sensor Description	Measurement Accuracy		
	Air Data Sensors	Air Speed (knots)	Altitude (feet)	
1	Silicon Pressure Transducer Honeywell	1.0	40.0	
2	Capacitive Pressure Transducer Rosemount	1.0	10.0	
3	Miniature Pressure Transducer Honeywell	15.0	80.0	
	Target Acquisition Radars	Azimuth (mrad)	Elevation (mrad)	Range (feet)
4	Fire Control Radar Emerson AN/APQ-159	1.5	3.0	1.0
5	Solid State Search Radar Texas Instruments AN/APQ-122	1.0	2.0	10.0
6	Navigation Radar System United Technology AN/APS-130	2.0	4.0	20.0
	Body Rate Sensors	Roll Rate (deg/hr)	Pitch Rate (deg/hr)	Yaw Rate (deg/hr)
7	Ring Laser Gyro Honeywell	0.01	0.01	0.01
8	Dry Tuned Rotor Gyro Litton	1.0	1.0	1.0
9	Vibrating Wire Rate Sensor	0.1	0.1	0.1
10	Fiber Optic Laser Gyro Honeywell	0.01	0.01	0.01
	Body Acceleration Sensors	Longitudinal Acceleration (mg)	Lateral Acceleration (mg)	Vertical Acceleration (mg)
11	Servoed Accelerometer Columbia SA107	0.1	0.1	0.1
12	Pendulous Accelerometer Sanders	0.1	0.1	0.1
13	Floated Pendulum Accelerometer Honeywell GG177	0.01	0.01	0.01
14	Pendulous Accelerometer Sundstrand 2160	0.02	0.02	0.02
15	Floated Pendulum Accelerometer Sundstrand QA2000	0.015	0.015	0.015

TABLE 34. SENSOR PHYSICAL PARAMETER DATA

No.	Sensor Description	Cost ($)	Weight (lbs)	Volume (C in)	Power (watts)	MTPI (hrs)
1	Silicon Pressure Transducer Honeywell	700.0	0.5	10.0	5.0	10000.0
2	Capacitive Pressure Transducer Rosemount	1000.0	0.5	12.0	5.0	1000.0
3	Miniature Pressure Transducer Honeywell	50.0	0.1	0.7	1.0	2000.0
4	Fire Control Radar Emerson AN/APQ-159	20000.0	130.0	4000.0	9000.0	4000.0
5	Solid State Search Radar Texas Instruments AN APQ-122	40000.0	200.0	6000.0	5000.0	1000.0
6	Navigation Radar System United Technology AN APS-130	15000.0	52.0	900.0	2000.0	2000.0
7	Ring Laser Gyro Honeywell	5000.0	3.5	34.0	4.0	1000.0
8	Dry Tuned Rotor Gyro Litton	3500.0	0.2	10.0	10.0	8000.0
9	Vibrating Wire Rate Sensor	300.0	0.22	2.6	20.0	2000.0
10	Fiber Optic Laser Gyro Honeywell	7000.0	0.5	5.2	1.0	2000.0
11	Servoed Accelerometer Columbia SA107	200.0	0.3	5.0	5.0	1000.0
12	Pendulous Accelerometer Sanders	720.0	0.15	1.1	2.0	3000.0
13	Floated Pendulum Accelerometer Honeywell GG177	5500.0	1.5	40.0	18.0	1000.0
14	Pendulous Accelerometer Sundstrand 2160	400.0	0.25	4.0	0.56	2000.0
15	Floated Pendulum Accelerometer Sundstrand QA2000	2200.0	1.5	30.0	10.0	1000.0

sensor selection procedure to determine the sensor candidate sets based on the eventual performance of the integrated control-of-flight system. A block diagram of the sensor selection procedure is shown in Figure 34.

The sensor set selection procedure reduces the number of possible candidate sensor sets to a manageable number, by using the projected measurement requirements and the sensor selection criteria. It considers all possible combinations of sensor sets and presents the designer with only a few candidate sets so that he can evaluate them with detailed performance analysis to make sure that they satisfy the mission performance. The description of the sensor selection algorithm is given in Appendix A and is summarized here as a three step process.

1. Form a baseline candidate sensor set with the most accurate sensors and with reliability requirements satisfied by using redundant sensors.
2. Generate candidate sensor sets whose accuracy or selection value is better than that of the baseline set.
3. Determine the sensor restrictions satisfied and present the candidate sensor sets according to the sensor selection value.

4.2.4 Navigation and Weapon Delivery Performance

The quality of sensors in the sensor candidate set is used to determine the mission performance. A block diagram of the steps in evaluating the performance of the mission is given in Figure 35. The navigation sensor quality and the mission trajectory are used by the navigation performance program (NAVCOV) to evaluate the navigation error (CEP) at the end of

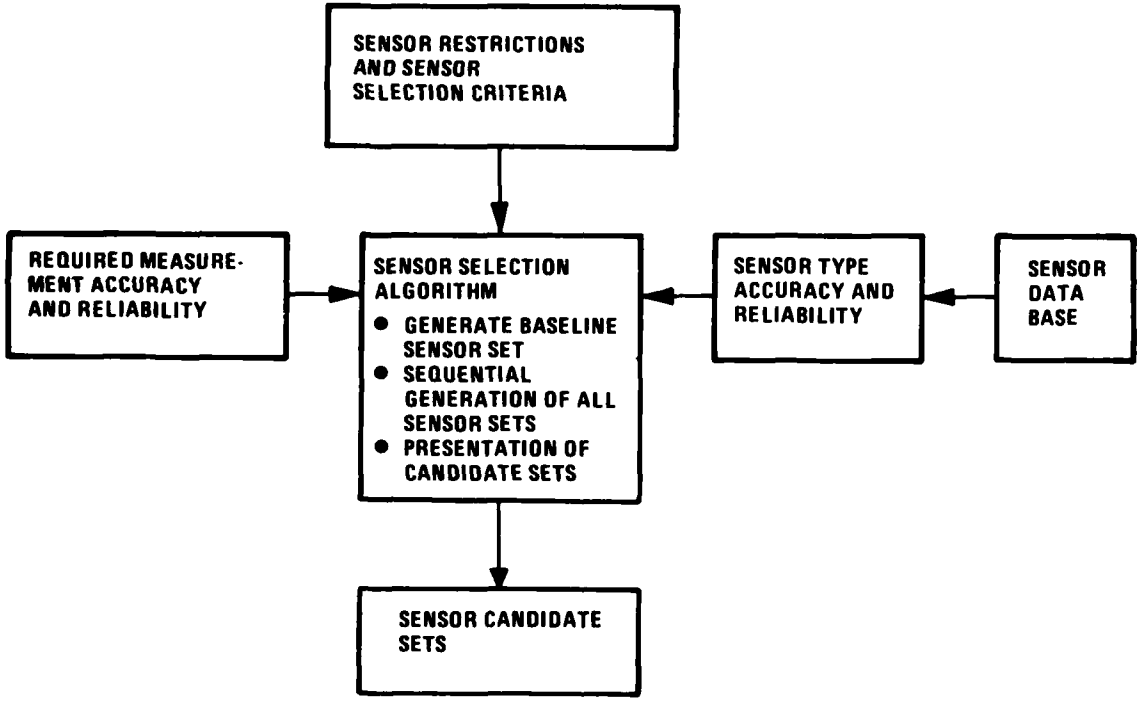


Figure 34. Sensor Candidate Set Generation Process

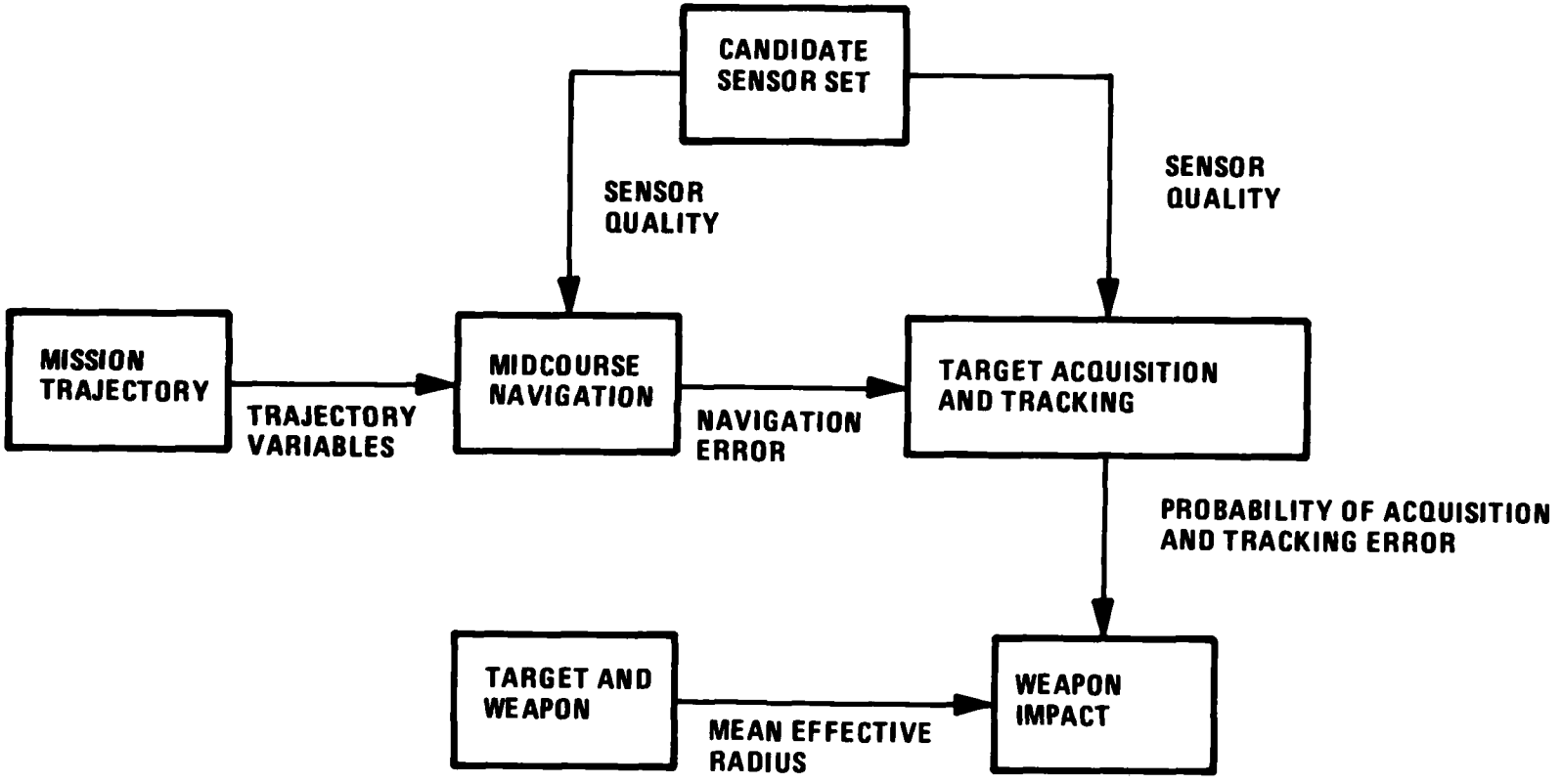


Figure 35. Mission Performance Evaluation Process

midcourse. This information and the target acquisition sensor quality are used to compute the probability of target acquisition and also the tracking error (CEP) until the weapon is released. Finally, the tracking error and the mean effective radius of the target-weapon combination are used to compute the probability of target kill, which is the mission performance.

Navigation performance is computed by using NAVCOV software developed by Honeywell (See Reference 28). NAVCOV is a covariance-based program and has proven effective in predicting the performance of inertial systems. The various sensor errors that can be used for propagating the covariance include bias errors, scale factor errors, misalignment errors, gyro g-sensitive errors, and accelerometer nonlinearity errors. Only bias errors were considered for the demonstration program to compute the navigation performance.

Weapon delivery performance is obtained by using the simplified models developed under this study to compute probability of acquisition and probability of target kill. These models are presented in Appendix B.

4.2.5 Interactive Program Implementation

The demonstration program consists of six modules (see Figure 36) organized as an overlayed or segmented program by the executive or main program to meet the interactive memory requirements. The interface between the user, the data base files, and the six program modules is shown in Figure 36. The interactive program is currently operational on two computers, Honeywell GCOS-B and the ASD computer (NOSBE). The segment load directives to set up the interactive program on the ASD computer are shown in Table 35.

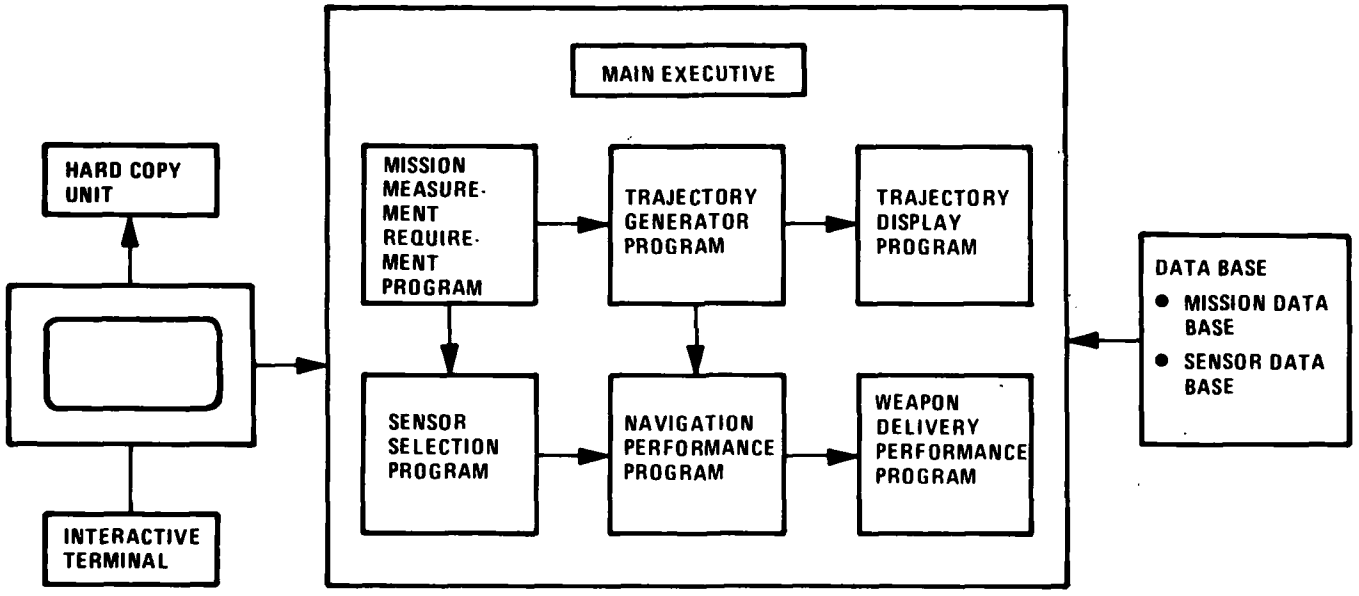


Figure 36. Interactive Program Organization

TABLE 35. SEGMENT LOAD DIRECTIVES TO SET UP THE INTERACTIVE PROGRAM

```
            GLOBAL      DBDV,LUD,MISSN,NAVERR,SCAT
            GLOBAL      SCOSTC,SCOSTP,SCOSTT,SCSET,SENSOR,STATUS
 ISIP       INCLUDE     NEWPAGE
 MREQ       INCLUDE     INPUTV,INPUT2,COF,WTGEN,WEAPON
 TGEN       INCLUDE     COMMAND,VALID,CINIT,CORIOL,DMATRX,DINIT
,,ANGLE,EQUATE,PTRAJ,EVINS
 SSEL       INCLUDE     STRTSC,GETSC,SEARCH,ADD,SUMR,SET,ORDER,REDUN,SAV
,,SSV,GENCS,ELIM,DELETE,ADJUST,CKCAN,STORE
,,SRV,PRINTC,SCCOST,COUNT,PRNTS,WNAV
 NAVCOV     INCLUDE     CINT,SMULT,SPMULT,DMULT,TRANS,MATRIX,DIAGMT
,,INTERP,PRINT,COEF,SPML2,TRNLI
 DPK        INCLUDE     TRAPI
 T          TREE        ISIP-(MREQ,TGEN,SSEL,NAVCOV,DPK,TKPLOT)
            END
```

The question and answer method of interaction was used in developing the demonstration program. All input from the user is in free format. At each step of the interaction, the program presents a menu of options and prompts the user to pick one of the options. In some instances the program prompts for a yes (y) or no (n) type of response.

In the following section a demonstration example is given to illustrate the sensor set design process.

4.2.6 Integrated Sensor Set Design Example

Use of the ICDT demonstration program is illustrated by designing integrated sensor sets for the air-to-ground conventional bomb delivery mission. The actual user/computer interaction for this example is given in detail in Appendix C. Here only the design process is explained.

The mission specifications used in the example are given in the following:

- Aircraft used = F-16
- Target = Ground-to-ground rocket
- Weapon = Mk 84
- Mean effective radius = 163 ft.
- Target kill probability = 0.8

The following are the trajectory parameters used to define the actual mission trajectory:

- Range to target 150 nm
- Cruise altitude 20000 ft
- Cruise speed 500 knots
- Weapon release altitude = 5000 ft

All three control-of-flight functions, namely, flight control, navigation, and weapon delivery, are chosen for sensor integration. The integrated measurement requirements are shown in Table 36. The sensor selection criterion is based on cost alone and the sensor set restrictions are as follows:

- Total cost = $50000
- Total weight = 400 lbs.
- Total volume = 6500 cin
- Total power = 10000 Watts

The integrated candidate sensor sets generated by the program are shown in Table 37. Since the sensor data base contains only four different types of sensors, the sets which contain more than four sensors have redundant sensors. Also note that the number of possible sensor sets (without considering redundancy) is given by 3 x 3 x 4 x 5 = 180 (based on the number of sensors of each type in the sensor data base). If redundancy is considered, the number of possible sensor sets would be even higher. The program presents only 24 sensor sets (see Table 37) for consideration

TABLE 36. INTEGRATED MEASUREMENT REQUIREMENTS

NO	MEASUREMENT	ACCURACY NEEDED	RELIABILITY NEEDED
1	AIRSPEED (KNOTS)	15.0000	.9800
2	ALTITUDE (FEET)	50.0000	.9800
3	AZIMUTH (MRAD)	1.7000	.9900
4	ELEVATION (MRAD)	3.2000	.9900
5	RANGE (FEET)	16.0002	.9900
6	ROLL RATE (DEG/HR)	.0800	.9980
7	PITCH RATE (DEG/HR)	.0800	.9980
8	YAW RATE (DEG/HR)	.0800	.9980
9	LONG ACCN (MG)	.0170	.9900
10	LATE ACCN (MG)	.0170	.9900
11	VERT ACCN (MG)	.0170	.9900

TABLE 37. INTEGRATED CANDIDATE SENSOR SETS

SET NUMBER	NUMBER OF SENSORS	SELECTION VALUE	RELIABILITY VALUE	ACCURACY VALUE	RESTRICTIONS SATISFIED
1	5	28700.0000	0.0086	0.2393	CHVP
2	5	29000.0000	0.0082	0.2968	CHVP
3	4	29900.0000	0.0082	0.3928	CHVP
4	4	30200.0000	0.0078	0.4504	CHVP
5	5	32000.0000	0.0086	0.3195	CHVP
6	5	32300.0000	0.0082	0.3771	CHVP
7	5	32900.0000	0.0086	0.3928	CHVP
8	4	33200.0000	0.0082	0.4730	CHVP
9	5	33200.0000	0.0082	0.4504	CHVP
10	4	33500.0000	0.0078	0.5306	CHVP
11	5	36200.0000	0.0086	0.4730	CHVP
12	5	36500.0000	0.0082	0.5306	CHVP
13	5	48700.0000	0.0087	0.3228	CHVP
14	5	49000.0000	0.0083	0.3804	CHVP
15	4	49900.0000	0.0084	0.4763	CHVP
16	4	50200.0000	0.0079	0.5339	HVP
17	5	52000.0000	0.0087	0.4030	HVP
18	5	52300.0000	0.0083	0.4606	HVP
19	5	52900.0000	0.0087	0.4763	HVP
20	4	53200.0000	0.0084	0.5566	HVP
21	5	53200.0000	0.0083	0.5339	HVP
22	4	53500.0000	0.0079	0.6141	HVP
23	5	56200.0000	0.0087	0.5566	HVP
24	5	56500.0000	0.0083	0.6141	HVP

of the designer. The sensor sets are all arranged according to the cost because the selection criterion was based on cost alone. Accuracy value gives an approximate feel for the performance capability of the sensor sets. The last column of Table 37 indicates which of the sensor set restrictions are satisfied.

To evaluate the mission performance, first sensor set number 1 with a total cost of $28,700 is chosen. The probability of kill obtainable with this set comes to only 0.1184. So a more accurate sensor set is needed to meet the performance specification. According to Table 37, candidate sensor set number 10 with a cost of $32,500 has the highest accuracy value and at the same time satisfies all the restrictions. With this set the probability of kill is 0.7867, which is close to the required mission performance (0.8). Table 37 shows that sensor set number 22 with a cost of $53,500 has the highest accuracy value of all the sets and with that set the probability of kill obtainable is 0.7967. The cost and performance of the above three sets are summarized in Table 38.

4.2.7 Integrated vs. Nonintegrated Design

It is possible to use the ICDT demonstration program to get an approximate indication of the differences between integrated and nonintegrated sensor set designs. If in the above example the sensor set design process is repeated each time with only one of the control-of-flight functions, then candidate sensor sets will be generated by the program for the nonintegrated COF functions separately. However, the mission performance cannot be evaluated since the sensor candidate sets are not complete individually to meet the measurement needs of the mission. If the lowest cost sensor

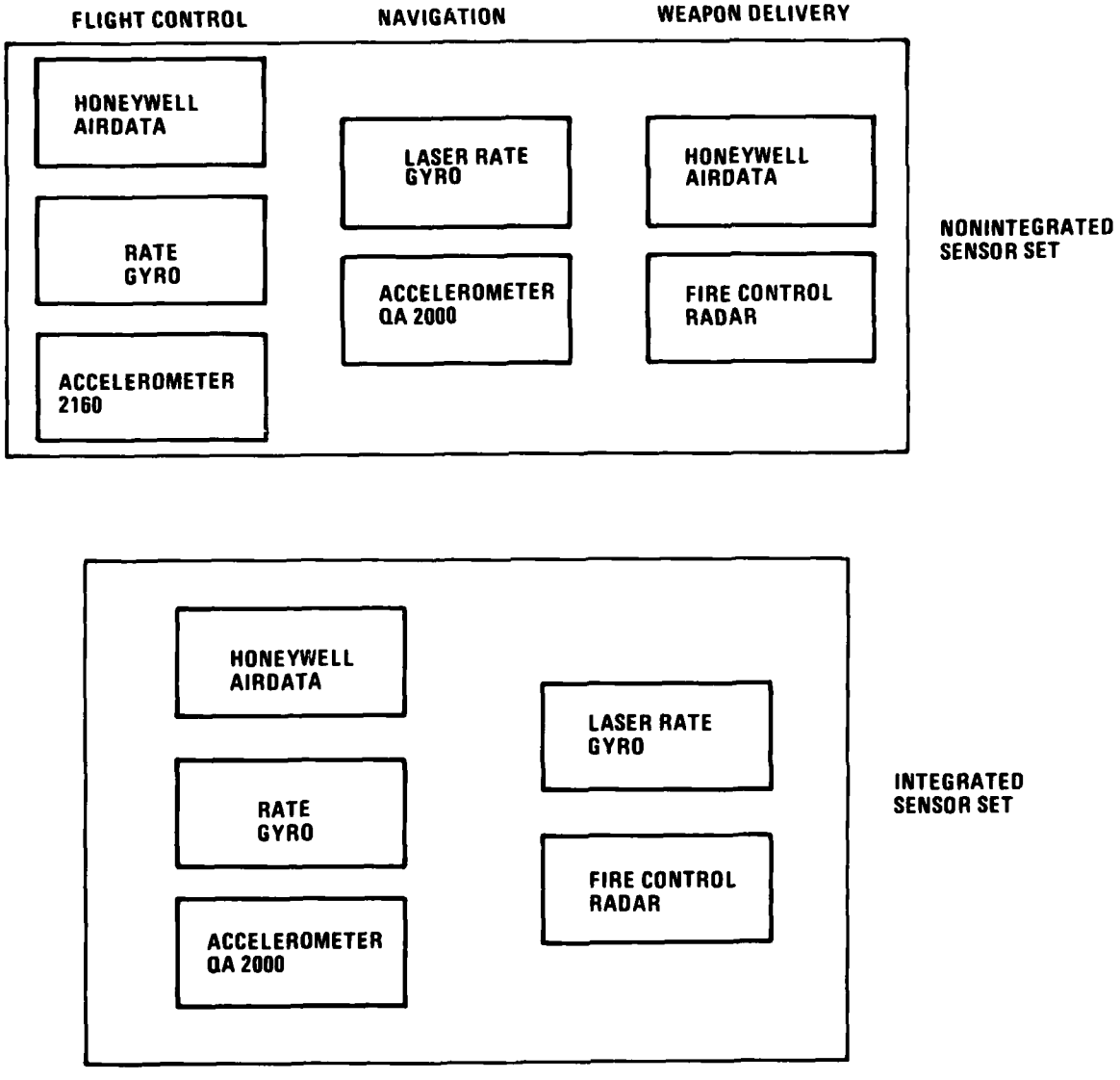
TABLE 38. INTEGRATED SENSOR SET PERFORMANCE

REQUIRED PROBABILITY OF KILL = 0.8

SENSOR SET #	TOTAL COST	PROBABILITY OF ACQUISITION	PROBABILITY OF KILL	RESTRICTION SATISFIED
1	$ 28,700	.2926	.1184	CWVP
10	$ 33,500	.9533	.7857	CWVP
22	$ 53,500	.9533	.7967	WVP

sets for each control-of-flight function are combined, then they can be compared with the lowest cost sensor set obtained for the integrated control-of-flight function. This comparison is shown in Table 39. In this example the integrated sensor set design results in the elimination of two sensor components.

TABLE 39. COMPARISON OF NONINTEGRATED SENSOR SET AND INTEGRATED SENSOR SET DESIGN



SECTION 5

RECOMMENDATIONS FOR FUTURE DEVELOPMENT

The current program identified and discussed the various techniques available for integrated control design and developed an approach (ICDT) for the integration of control-of-flight systems. The techniques are summarized in Table 40. A methodology was developed for integrated sensor set design and was demonstrated on an interactive computer. Any future development should start from this foundation and extend the methodologies and the data bases for effectively designing integrated control design for future tactical aircrafts. The specific recommendations for the next phase of development are given in the following:

- Model and Algorithm Development
  - --Develop reliability analysis model for hybrid system architectures (hardware + software)
  - --Develop algorithms for redundancy management schemes (analytic redundancy, fault detection, hardware redundancy, etc.) with consideration for reliability, survivability, and performance
  - --Develop algorithms for integrated computational schemes (simplified Kalman filters) to improve reliability and performance

TABLE 40. DESIGN, EVALUATION, AND COST MODELS RECOMMENDED

METHODOLOGY STEPS	EFFECTIVENESS PARAMETERS							COST PARAMETERS	
	PERFORMANCE/CAPABILITY		RELIABILITY/DEPENDABILITY		MAINTAINABILITY/ AVAILABILITY		SURVIVABILITY	ACQ.	O&S
2. DERIVATION OF FUNCTIONAL REQUIREMENTS	• NAVCOV • KONPACT • ADAP								
3G. IMPLEMENTATION DESIGN OF SENSORS AND ACTUATORS	• PLEDGER'S MATCHUP	• VISUAL DISPLAY AND CONTROL *INTEGRATION*	MTBF	• SIMPLIFIED SESIP	$\frac{MTBF}{MTBF+MDT}$	• SIMPLIFIED GEMM	• SIMPLIFIED SUDIC	PRICE H	PRICE L
3B,C. D&E IMPLEMENTATION DESIGN OF DATA PROCESSING SUBSYSTEM	• FSM • HDM • HIPO		(D.P. HDWE) MTBF (SOFTWARE)	• SIMPLIFIED SESIP • FSM	$\frac{MTBF}{MTBF+MDT}$	• SIMPLIFIED GEMM	• SIMPLIFIED SUDIC	PRICE H PRICE S	PRICE L PRICE S3 BOEING CLMM
3i. SUBSYSTEMS INTERFACING DESIGN			MTBF	• SIMPLIFIED SESIP	$\frac{MTBF}{MTBF+MDT}$	• SIMPLIFIED GEMM	• SIMPLIFIED SUDIC	PRICE H	PRICE L
4A. EFFECTIVENESS EVALUATION	FROM DESIGN STEPS	• QUEING THEORY • WORKLOAD ANALYSIS	(HARDWARE) MTBF (SOFTWARE)	• SESIP • FSM VERIFICATION		• GEMM	• SUDIC		

- --Generalize the sensor selection algorithms to include criteria for selecting architecture, redundancy management, and integrated computation schemes along with sensors
- --Develop techniques for in-flight effectiveness measurement and management

- Data Base Development
  - --Develop a first-level architecture data base with consideration for reliability, survivability, and performance; include failure rate data for different architectures
  - --Expand the current sensor data base to include terrain following sensors, GPS and other radio sensors; include MTBF and vulnerability data for sensors
  - --Include actuators and data processing functions in the data base

- Performance Evaluation
  - --Refine the algorithms for system effectiveness evaluation using the extended WSIEAC approach
  - --Parameter/structural sensitivity analysis
  - --Develop simplified algorithms for computing probability of kill (P_k) and probability of survival (P_s) for the selected mission
  - --Develop simplified algorithms for computing the life-cycle cost
  - --Develop simplified algorithms for survivability evaluation using simple threat models and vulnerability data for sensors and other hardware

--Develop algorithms for reliability evaluation using SESIP approach which utilizes MTBF data for sensors and failure rates for architectures

--Develop simplified algorithms for evaluating dependability, availability, and capability of the system.

- Demonstrate ICDT on future tactical aircraft
  --Develop mission data base for generic fighter
  --Develop system architecture
  --Optimize life-cycle cost

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APPENDIX A

SENSOR SELECTION ALGORITHMS

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SENSOR SELECTION ALGORITHMS

INTRODUCTION

The problem of selecting sensor candidate sets, for the purpose of evaluating them for sensor integration, is an important one. The brute force approach, in which all possible combinations of sensors are considered, leads to a very large number of candidate sets making them almost impossible to evaluate. Consider, for example, a control-of-flight system which needs N independent sensor measurements. If the sensor data base contains 10 different sensors for each of these measurements, then the number of possible sensor combinations is given by 10^N. Thus the need exists for a sensor selection procedure to determine the sensor candidate sets based on the eventual performance of the integrated control-of-flight system.

In the following a sensor selection procedure is presented, based on reliability and accuracy considerations, to reduce the possible sensor sets to a manageable number. In addition, a sensor selection value, based on the weighted sum of cost, weight, volume, and power requirements of the sensors, is used to aid in the selection procedure. In the following, the definitions of various quantities used and their calculations are described first. This is followed by a detailed description of the sensor selection procedure.

MEASUREMENT ACCURACY AND RELIABILITY VECTORS

These are represented by vectors a_r and r_r and the elements $a_r(j)$ and $r_r(j)$ correspond to the measurement accuracy and reliability required for the parameter j to be measured for the mission. The list of parameters to be measured and the measurement accuracy and reliability values for the conventional weapon delivery mission are given in Tables 31 and 32. As an example, j = 2 corresponds to the altitude parameter and the values of $a_r(2)$ and $r_r(2)$ for the flight control function are given by 50.0 ft and 0.98.

SENSOR ACCURACY AND RELIABILITY MATRIXES

These are represented by matrixes A_s and R_s and the elements $A_s(j, i)$ and $R_s(j, i)$ correspond to the i^{th} sensor accuracy and reliability with respect to the parameter j. Since it is normal practice to specify mean time between failures (MTBF) data for the sensors, a simple procedure is used to calculate the reliability of the sensors and is given in the following.

RELATIONSHIP BETWEEN MTBF DATA AND RELIABILITY OF SENSORS

The probability that a sensor will fail at time t during its operation (assuming normal distribution) is given by

$$p_f = \frac{1}{2\pi\sigma} e^{-\frac{(t-\mu)^2}{2\sigma^2}} \qquad (1a)$$

where μ is the mean time between failures (MTBF)

σ is the standard deviation

Since sensor reliability is characterized by MTBF data, we will assume that the standard deviation σ is proportional to MTBF (μ). Now, if the duration of the mission is at Δt, then the maxiumum probability that the sensor will fail during the mission is given by

$$p_f = \int_{\mu - \frac{\Delta t}{2}}^{\mu + \frac{\Delta t}{2}} \frac{k}{\sqrt{2\pi}\,\mu} e^{-k^2 \frac{(t-\mu)^2}{2\mu^2}} dt \qquad (1b)$$

which can be simplified to

$$p_f = \frac{k}{\sqrt{2\pi}\,\mu} \Delta t \qquad (1c)$$

and the sensor reliability is given by

$$r = 1 - p_f \qquad (1d)$$

This simple relationship is used to determine the sensor reliability from MTBF data and mission duration.

SENSOR SET ACCURACY AND RELIABILITY VECTORS

Since we are dealing with sensor sets and, in general, a sensor set will consist of more than one sensor, it is necessary to integrate the individual sensor accuracies and reliabilities into a sensor set accuracy and reliability. This will later facilitate comparisons between sensor sets.

The sensor set accuracy and reliability vectors are represented by a_s and r_s and the elements $a_s(j)$ and $r_s(j)$ correspond to the sensor set accuracy and reliability for the parameter j.

If there are n sensors in the sensor set which measures parameter j, then the probability that measurement parameter j is not available is given by[54]

$$P_s(j) = \prod_{i=1}^{n} P_s(j, i) \tag{2}$$

where $P_s(j, i)$ is the probability of i^{th} sensor failure to measure parameter j and is given by

$$P_s(j, i) = 1 - R_s(j, i) \tag{3}$$

Hence the reliability of measurement parameter j for the sensor set is given by

$$r_s(j) = 1 - P_s(j) \tag{4}$$

---

[54] A. Papoulis, Probability, Random Variables and Stochastic Processes, McGraw Hill, 1965.

The accuracy of measurement parameter j for the sensor set is computed as a reliability weighted number and is given by

$$a_s(j) = \frac{\sum_{i=1}^{n} A_s(j, i)\, P_s(j, i)}{\sum_{i=1}^{n} P_s(j, i)} \tag{5}$$

For example, if there are two sensors in a sensor set which measure the altitude with accuracies of 40 ft and 10 ft and reliabilities of 0.9 and 0.8 respectively, then the accuracy and reliability value of the sensor set for altitude measurement is given by

$$a_s(2) = \frac{40 \times 0.9 + 10 \times 0.8}{0.9 + 0.8} = 25.9 \text{ ft} \tag{6}$$

$$r_s(2) = 1 - (1 - 0.9)(1 - 0.8) = 0.98 \tag{7}$$

SENSOR SET ACCURACY, RELIABILITY, AND SELECTION VALUES

As a further aid in the sensor set selection procedure the following quantities are defined. Sensor set accuracy value is an indicator of excess accuracy of the sensor set and is defined by the following expression

$$a_s = \sum_{j=1}^{m} \frac{a_r(j) - a_s(j)}{a_r(j)} \tag{8}$$

where m is the number of measurements.

Sensor set reliability value is an indicator of excess reliability of the sensor set and is defined by the following expression

$$r_s = \sum_{j=1}^{m} r_s(j) - r_r(j) \qquad (9)$$

In addition to accuracy and reliability, sensors are characterized by cost, weight, volume, and power requirements. Sensor set selection value is a collective indicator of these characteristics and is defined by

$$J = \sum_{i=1}^{n} w_c \times c(i) + w_w \times w(i) + w_v \times v(i) + w_p \times p(i) \qquad (10)$$

where n is the number of sensors in the sensor set, w_c, w_w, w_v, and w_p are the weightings on cost, weight, volume, and power respectively, and c(i), w(i), v(i) and p(i) are the actual cost, weight, volume, and power requirements of sensor i.

SENSOR SELECTION PROCEDURE

The purpose of the sensor selection procedure is to consider all possible combinations of sensor sets and present the designer with only a few candidate sets so that he can evaluate them with detailed performance analysis to make sure that they satisfy the performances required by the mission.

In the following the sensor selection procedure is described as a three step process. The organization of the procedure is presented in Figure A-1. The first step generates a base line candidate set; the second step generates all combinations of sensor sets and compares then with the base line set, and the third step presents the candidate sets to the designer.

In the first step, sensors (i) whose accuracies $A_s(j, i)$ are not within a specified band of the required measurement accuracies $a_r(j)$ for any of the parameters j are eliminated from further consideration. This reduces the number of sensor set combinations that need to be considered. Next a baseline candidate set with the best accuracies available among the remaining sensors is generated and is displayed to the designer. Finally, redundant sensors are introduced into the baseline candidate set if necessary to satisfy the required measurement reliabilities $r_r(j)$ for all j. Up to a maximum of four redundant sensors are allowed.

In the second step, all possible combinations of sensor sets are generated. Those sensor sets which do not satisfy the measurement accuracy requirements are dropped from further consideration. Redundant sensors are added if necessary to meet measurement reliability requirements. Those sensor sets whose selection value is better than that of the baseline set are retained as candidate sensor sets.

In the third step, the candidate sensor sets are further checked to see if they meet the sensor set restrictions on cost, weight, volume, and power. The candidate sets are ordered according to the selection value and presented to the designer for sensor set performance evaluation.

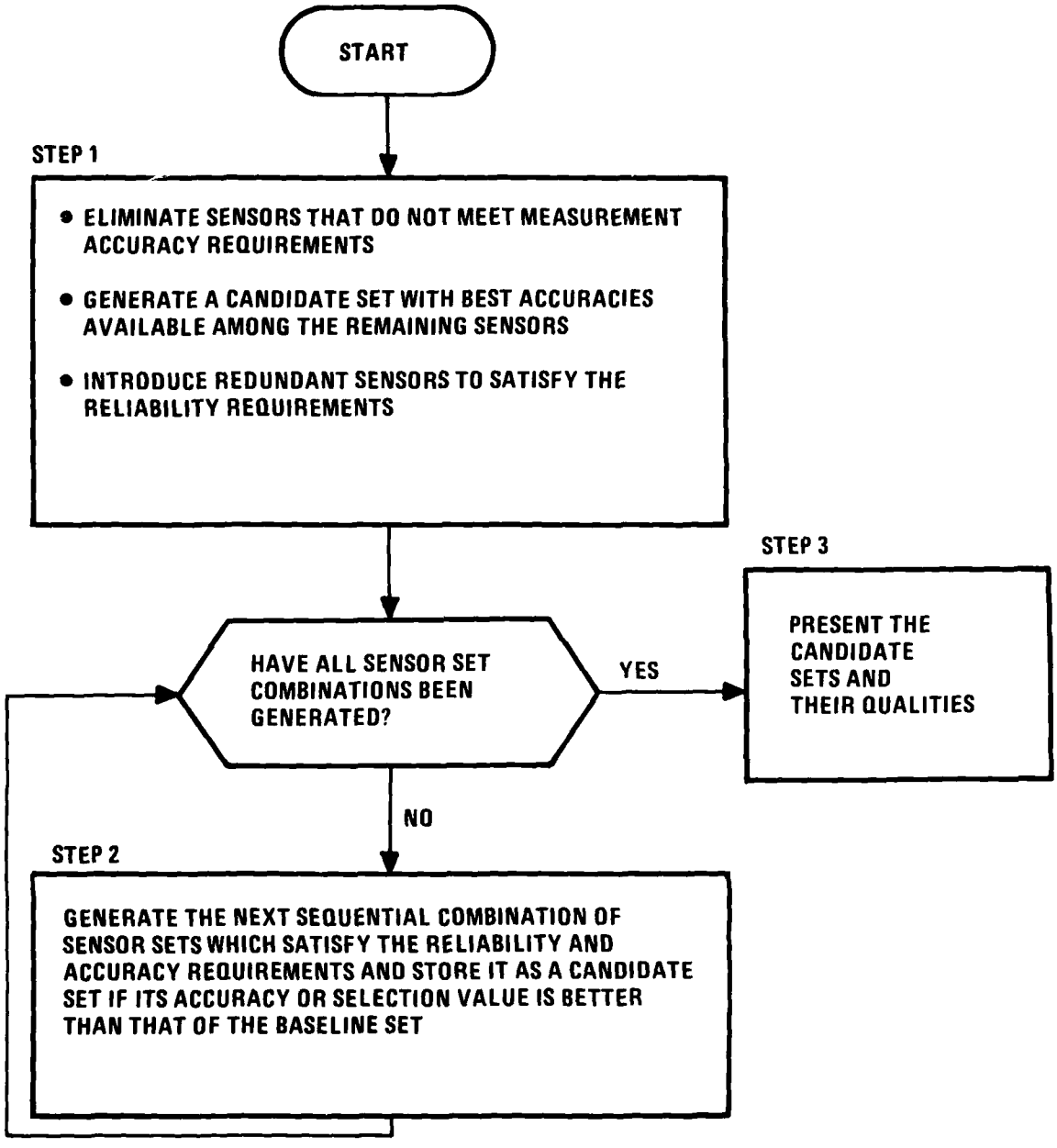


Figure A-1. Organization of the Three Step Procedure for Sensor Selection

APPENDIX B

WEAPON DELIVERY PERFORMANCE MODELS

APPENDIX B

WEAPON DELIVERY PERFORMANCE MODELS

Simplified models for computing probability of acquisition and probability of target kill are presented in the following. These models assume that the weapon is delivered during level maneuver.

ACQUISITION PROBABILITY MODEL

Given a sensor with $\pm\ \theta_1$ in elevation and $\pm\ \theta_2$ in azimuth, with a nominal depression angle γ in search, the probability that the desired target is in the field of view at a designated time, t, is dependent upon the navigation accuracies (θ_1, θ_2 and γ in radians).

Let σ_{NR} be the navigation error along the line from the designated search point to the expected target position, and σ_{NXR} be the error at right angles to this line.

The probability that the target is within the lateral search limits is:

$$P_{XR} = 2 \int_{o}^{\frac{(H_A/\sin\gamma)*\theta_2}{\sigma_{NXR}}} \frac{1}{\sqrt{2\pi}}\, e^{-x^2/2}\, dx \qquad (9)$$

The probability that the target is within the down range search limits for a snapshot search is:

$$P_R = \int_{\frac{-H_A \sin(\gamma+\theta_1)}{\sigma_{NR}}}^{\frac{H_A \sin(\gamma-\theta_1)}{\sigma_{NR}}} \frac{1}{\sqrt{2\pi}} e^{-x^2/2} \, dx \qquad (10)$$

If the search is to be conducted for a time t, in advance of having the expected target in the center of the FOV, until a time t_2 after the expected target was at the center of the field of view, the probability becomes:

$$P_R' = \int_{-(H_A \sin(\gamma+\theta_1) + t_1 \cdot V_A)/\sigma_{NR}}^{(HA \cdot \sin(\gamma-\theta_1) + t_2 \cdot V_A)/\sigma_{NR}} \frac{1}{\sqrt{2\pi}} e^{-x^2/2} \, dx \qquad (11)$$

Total probability of acquisition thus becomes

$$P_T = P_{XR} \times P_R \text{ or } P_{XR} \times P_R' \qquad (12)$$

In practice, the limits on the FOV also depend upon the ability of the delivery system to engage a detected target. Detections made outside the engagement envelope are not true acquisitons, although such detections could reduce σ_{NR} and σ_{XR} for a subsequent acquisition.

TARGET PROBABILITY OF KILL MODEL

Given the nominal parameters for conventional weapon delivery

H_A Altitude (feet)

V_A Airspeed (fps)

R_S Slant range at release (ft)

TOF Time of fall (see)

θ_F Terminal impact angle (°)

and the various errors (1 sigma values) associated with weapon delivery

ΔH_A Altitude error (ft)

ΔV_{AZ} Vertical velocity error (fps)

ΔV_{AY} Lateral velocity error (fps)

ΔV_{AX} Airspeed error (fps)

$\Delta \phi_R$ Roll angle error (rad)

$\Delta \phi_P$ Pitch angle error (rad)

$\Delta \phi_Y$ Yaw angle error (rad)

ΔR_S Slant range error (ft)

$\Delta \psi_D$ Depression angle error (rad)

$\Delta \psi_A$ Azimuth angle error (rad)

$\Delta \beta$ Ballistic error (rad)

ΔV_W Wind error (fps)

ΔT_R Timing error at release (sec)

the following range and cross range error components can be defined.

$$\epsilon_1 = \frac{\Delta H_A}{H_A} \cdot TOF \cdot V_A \cdot \cos \theta_F \qquad \text{(range comp)}$$

$$\epsilon_2 = \Delta V_{AZ} \cdot TOF \cdot \sin \theta_F \qquad \text{(range comp)}$$

$$\epsilon_3 = \Delta V_{AY} \cdot TOF \qquad \text{(cross range comp)}$$

$$\epsilon_4 = \Delta V_{AX} \cdot TOF \qquad \text{(range comp)}$$

$$\epsilon_5 = \Delta \phi_R \cdot H_A \qquad \text{(cross range comp)}$$

$$\epsilon_6 = \Delta \phi_P \, R_s^2 / H_A \qquad \text{(range comp)}$$

$$\epsilon_7 = \Delta \phi_Y \cdot \sqrt{R_s^2 - H_A^2} \qquad \text{(cross range comp)}$$

$$\epsilon_8 = \Delta R_S \cdot R_S / \sqrt{R_s^2 - H_A^2} \qquad \text{(range comp)}$$

$$\epsilon_9 = \Delta \psi_D \cdot R_S^2 / H_A \qquad \text{(range comp)}$$

$$\epsilon_{10} = \Delta \psi_A \cdot \sqrt{R_S^2 - H_A^2} \qquad \text{(cross range comp)}$$

$$\epsilon_{11} = \Delta \beta \cdot R_S / \sin \theta_F \qquad \text{(range comp)}$$

$$\epsilon_{12} = \Delta \beta \cdot R_S \qquad \text{(cross range comp)}$$

$$\epsilon_{13} = \Delta V_W \cdot TOF \qquad \text{(range \& cross range comp)}$$

$$\epsilon_{14} = \Delta T_R \cdot V_A \qquad \text{(range comp)}$$

Then the impact CEP is given by

$$\sigma_R = \sqrt{\epsilon_1^2 + \epsilon_2^2 + \epsilon_4^2 + \epsilon_6^2 + \epsilon_8^2 + \epsilon_9^2 + \epsilon_{11}^2 + \epsilon_{13}^2 + \epsilon_{14}^2} \qquad (14)$$

$$\sigma_{XR} = \sqrt{\epsilon_3^2 + \epsilon_5^2 + \epsilon_7^2 + \epsilon_{10}^2 + \epsilon_{12}^2 + \epsilon_{13}^2} \qquad (15)$$

$$CEP = 1.1774\sqrt{\sigma_R^2 + \sigma_{XR}^2} \qquad (16)$$

and the components of the probability of kill is computed by

$$P_{KA} = 2 \int_0^{\frac{MER}{\sigma_R}} \frac{1}{\sqrt{2\pi}} e^{-x^2/2} \, dx \qquad (17)$$

$$P_{KB} = 2 \int_0^{\frac{MER}{\sigma_{XR}}} \frac{1}{\sqrt{2\pi}} e^{-x^2/2} \, dx \qquad (18)$$

where MER is the mean effective radius of the target-weapon combination. Finally the target probability of kill is given by

$$P_{KT} = P_{KA} \cdot P_{KB} \qquad (19)$$

The above probability models are used for computing the weapon delivery performance.

APPENDIX C

DEMONSTRATION OF THE INTERACTIVE PROGRAM FOR INTEGRATED SENSOR SET DESIGN

*** SENSOR INTEGRATION PROGRAM ***

THIS PROGRAM WAS DEVELOPED TO DEMONSTRATE THE DESIGN OF INTEGRATED AVIONIC SENSORS FOR FIGHTER AIRCRAFT. IT HAS THE FOLLOWING CAPABILITIES:

1. GENERATE MEASUREMENT REQUIREMENTS OF THE INTEGRATED SENSOR FUNCTIONS FOR THE SPECIFIED MISSION

2. SELECT THE SENSOR CANDIDATE SETS FROM THE SENSOR DATA BASE TO SATISFY THE MEASUREMENT REQUIREMENTS

3. EVALUATE THE MISSION PERFORMANCE OF THE SELECTED SENSOR CANDIDATE SET

HIT CARRIAGE RETURN TO CONTINUE !

```
*** MISSION SPECIFICATION ***
MISSION = AIR TO GROUND (CONVENTIONAL BOMB)
AIRCRAFT =  F16 - ADVANCED FIGHTER
TARGET = GROUND TO GROUND ROCKET FROG 4
WEAPON = MK84
KILL PROBABILITY =  .800
MODIFY MISSION SPECIFICATION ?N
```

*** MISSION PARAMETERS ***

NO	PARAMETER	VALUE
1	RANGE TO TARGET	150.00 NM
2	CRUISE ALTITUDE	20000.00 FT
3	WEAPON RELEASE ALTITUDE	5000.00 FT
4	CRUISING SPEED	500.00 KNOT

MODIFY MISSION PARAMETERS ?N

*** AIRCRAFT PARAMETERS ***

NO	PARAMETER	VALUE
1	MAXIMUM RANGE	2000.00 NM
2	MAXIMUM SPEED	700.00 KNOT
3	MINIMUM CRUISING SPEED	500.00 KNOT
4	MAX CRUISING ALTITUDE	50000.00 FT
5	MIN CRUISING ALTITUDE	10000.00 FT
6	MAXIMUM ACCELERATION	20.00 G

MODIFY AIRCRAFT PARAMETERS ?N

*** COF FUNCTIONS ***

NO	CONTROL OF FLIGHT (COF) FUNCTIONS
1	FLIGHT CONTROL (FC)
2	GUIDANCE & NAVIGATION (GN)
3	WEAPON DELIVERY (WD)

SELECT COF FUNCTIONS FOR SENSOR SELECTION !1,2,3

*** MISSION MEASUREMENT REQUIREMENTS ***

NO	MEASUREMENT	ACCURACY NEEDED	RELIABILITY NEEDED
1	AIRSPEED (KNOTS)	15.0000	.9800
2	ALTITUDE (FEET)	50.0000	.9800
3	AZIMUTH (MRAD)	1.7000	.9900
4	ELEVATION (MRAD)	3.2000	.9900
5	RANGE (FEET)	16.0000	.9900
6	ROLL RATE (DEG/HR)	.0800	.9980
7	PITCH RATE (DEG/HR)	.0800	.9980
8	YAW RATE (DEG/HR)	.0800	.9980
9	LONG ACCN (MG)	.0170	.9900
10	LATE ACCN (MG)	.0170	.9900
11	VERT ACCN (MG)	.0170	.9900

MODIFY MEASUREMENT REQUIREMENTS ?N

*** SENSOR SELECTION CRITERIA ***

NO	PARAMETER	WEIGHTING FACTOR
1	COST	1.00
2	WEIGHT	0.00
3	VOLUME	0.00
4	POWER	0.00

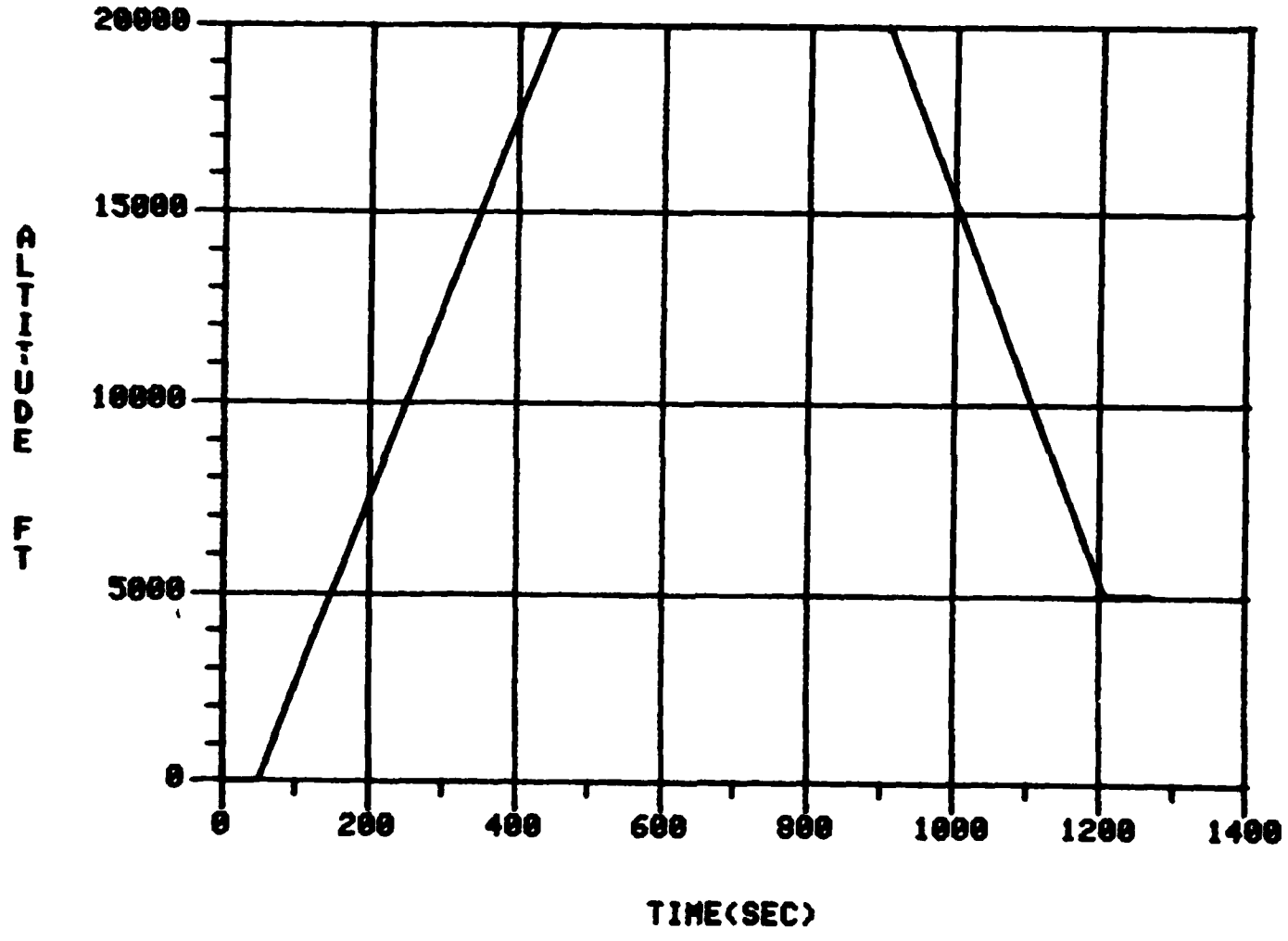
MODIFY SELECTION CRITERIA ?N

*** SENSOR PARAMETERS ***

NO	PARAMETER	VALUE	
1	TOTAL COST	50000.00	DOL
2	TOTAL WEIGHT	400.00	LB
3	TOTAL VOLUME	6500.00	CIN
4	TOTAL POWER	10000.00	WATT
5	POWER SUPPLY VOLTAGE	110.00	V
6	POWER SUPPLY FREQUENCY	400.00	C/S

MODIFY SENSOR PARAMETERS ?N

```
*** TGEN EXECUTING ***
DISPLAY FLIGHT PATH FOR MISSION ?Y
ENTER BAUD RATE OF DISPLAY !300
```


20000
15000
10000
5000
0
ALTITUDE FT
0
200
400
600
800
1000
1200
1400
TIME(SEC)

*** BASELINE ACCURACY FOR GENERATION OF SENSOR SET COMBINATIONS ***

MEASUREMENT	SENSOR NO	MEASUREMENT ACCURACY NEEDED	SENSOR ACCURACY
AIRSPEED (KNOTS)	2	15.0000	1.0000
ALTITUDE (FEET)	2	50.0000	10.0000
AZIMUTH (MRAD)	5	1.7000	1.0000
ELEVATION (MRAD)	5	3.2000	2.0000
RANGE (FEET)	5	16.0000	10.0000
ROLL RATE (DEG/HR)	7	.0800	.0100
PITCH RATE (DEG/HR)	7	.0800	.0100
YAW RATE (DEG/HR)	7	.0800	.0100
LONG ACCN (MG)	13	.0170	.0100
LATE ACCN (MG)	13	.0170	.0100
VERT ACCN (MG)	13	.0170	.0100

HIT CARRIAGE RETURN TO CONTINUE !

*** SEQUENTIAL GENERATION OF SENSOR CANDIDATE SETS ***

2	5	7	7	13
1	5	7	7	13
2	4	7	7	13
1	4	7	7	13
2	5	7	9	13
1	5	7	9	13
2	4	7	9	13
1	4	7	9	13
2	5	10	13	
1	5	10	13	
2	4	10	13	
1	4	10	13	
2	5	7	7	15
1	5	7	7	15
2	4	7	7	15
1	4	7	7	15
2	5	7	9	15
1	5	7	9	15
2	4	7	9	15
1	4	7	9	15
2	5	10	15	
1	5	10	15	
2	4	10	15	
1	4	10	15	

HIT CARRIAGE RETURN TO CONTINUE !

*** SENSOR CANDIDATE SETS ***

SET NUMBER	NUMBER OF SENSORS	SELECTION VALUE	RELIABILITY VALUE	ACCURACY VALUE	RESTRICTIONS SATISFIED
1	5	28700.0000	0.0086	0.2393	CWVP
2	5	29000.0000	0.0082	0.2968	CWVP
3	4	29900.0000	0.0082	0.3928	CWVP
4	4	30200.0000	0.0078	0.4504	CWVP
5	5	32000.0000	0.0086	0.3195	CWVP
6	5	32300.0000	0.0082	0.3771	CWVP
7	5	32900.0000	0.0086	0.3928	CWVP
8	4	33200.0000	0.0082	0.4730	CWVP
9	5	33200.0000	0.0082	0.4504	CWVP
10	4	33500.0000	0.0078	0.5306	CWVP
11	5	36200.0000	0.0086	0.4730	CWVP
12	5	36500.0000	0.0082	0.5306	CWVP
13	5	48700.0000	0.0087	0.3228	CWVP
14	5	49000.0000	0.0083	0.3804	CWVP
15	4	49900.0000	0.0084	0.4763	CWVP
16	4	50200.0000	0.0079	0.5339	WVP
17	5	52000.0000	0.0087	0.4030	WVP
18	5	52300.0000	0.0083	0.4606	WVP
19	5	52900.0000	0.0087	0.4763	WVP
20	4	53200.0000	0.0084	0.5566	WVP
21	5	53200.0000	0.0083	0.5339	WVP
22	4	53500.0000	0.0079	0.6141	WVP
23	5	56200.0000	0.0087	0.5566	WVP
24	5	56500.0000	0.0083	0.6141	WVP

SELECT SENSOR CANDIDATE SET ?1

*** SENSOR CANDIDATE SET # 1 ***

NO	SENSOR DESCRIPTION	MULT	COST	WEIGHT	VOLUME	POWER
1	SILICON PRESSURE TRANSDUCER HONEYWELL	1	700.00	0.90	10.00	5.00
4	FIRE CONTROL RADAR EMERSON AN/APQ-159	1	20000.00	130.00	4000.00	9000.00
7	RING LASER GYRO HONEYWELL	1	5000.00	3.50	84.00	4.00
9	VIBRATING WIRE RATE SENSOR	1	800.00	0.22	2.60	20.00
15	FLOATED PEND ACC SUNDSTRAND QA2000	1	2200.00	1.50	30.00	10.00
	TOTAL NUMBER SENSORS	5	28700.00	136.12	4126.60	9039.00
	RESTRICTIONS		50000.00	400.00	6500.00	10000.00

HIT CARRIAGE RETURN TO CONTINUE !

*** SENSOR CANDIDATE SET # 1 ***

MEASUREMENT	MEASUREMENT ACCURACY NEEDED	SENSOR ACCURACY	MEASUREMENT RELIABILITY NEEDED	SENSOR RELIABILITY
AIRSPEED (KNOTS)	15.0000	1.5000	0.9800	0.9997
ALTITUDE (FEET)	50.0000	40.0000	0.9800	0.9997
AZIMUTH (MRAD)	1.7000	1.5000	0.9900	0.9993
ELEVATION (MRAD)	3.2000	3.0000	0.9900	0.9993
RANGE (FEET)	16.0000	15.0000	0.9900	0.9993
ROLL RATE (DEG/HR)	0.0800	0.0550	0.9900	1.0000
PITCH RATE (DEG/HR)	0.0800	0.0550	0.9900	1.0000
YAW RATE (DEG/HR)	0.0800	0.0550	0.9900	1.0000
LONG ACCN (MG)	0.0170	0.0150	0.9900	0.9972
LATE ACCN (MG)	0.0170	0.0150	0.9900	0.9972
VERT ACCN (MG)	0.0170	0.0150	0.9900	0.9972

DO YOU WANT PERFORMANCE OF THIS SENSOR SET ?Y

*** SENSOR CANDIDATE SET # 1 ***

RELEASE ALTITUDE (FT)	=	5000.00
AIRSPEED (FPS)	=	844.50
SLANT RANGE AT RELEASE (FT)	=	7071.07
TIME OF FALL (SEC)	=	24.92
TERMINAL IMPACT ANGLE (DEG)	=	45.00
ALTITUDE ERROR (FT)	=	40.0000
VERTICAL VELOCITY ERROR (FPS)	=	0.1054
LATERAL VELOCITY ERROR (FPS)	=	5.5717
AIRSPEED ERROR (FPS)	=	5.5734
ROLL ANGLE ERROR (MRAD)	=	0.2129
PITCH ANGLE ERROR (MRAD)	=	0.2129
YAW ANGLE ERROR (MRAD)	=	0.3614
SLANT RANGE ERROR (FT)	=	15.0000
DEPRESSION ANGLE ERROR (MRAD)	=	3.0000
AZIMUTH ANGLE ERROR (MRAD)	=	1.5000
BALLISTIC ERROR (MRAD)	=	6.0000
WIND ERROR (FPS)	=	1.0000
TIMING ERROR AT RELEASE (SEC)	=	0.1000
NAVIGATION TRACK SIGMA (FT)	=	2613.36
NAVIGATION CROSS-TRACK SIGMA (FT)	=	2612.44
RANGE SIGMA (FT)	=	214.89
CROSS-RANGE SIGMA (FT)	=	147.53
WEAPON DELIVERY CEP (FT)	=	306.90
MEAN EFFECTIVE RADIUS OF WEAPON (FT)	=	163.38

PROBABILITY OF ACQUISITION=0.2926
PROBABILITY OF KILL GIVEN ACQUISITION=0.4047
COMPUTED PROBABILITY OF KILL=0.1184

SELECT SENSOR CANDIDATE SET ?10

*** SENSOR CANDIDATE SET # 10 ***

NO	SENSOR DESCRIPTION	MULT	COST	WEIGHT	VOLUME	POWER
2	CAPACITIVE PRESSURE TRANS ROSEMOUNT	1	1000.00	0.90	12.00	5.00
4	FIRE CONTROL RADAR EMERSON AN/APQ-159	1	20000.00	130.00	4000.00	9000.00
10	FIBER OPTIC LASER GYRO HONEYWELL	1	7000.00	0.50	3.20	1.00
13	FLOATED PEND ACC HONEYWELL GG177	1	5500.00	1.50	40.00	10.00
	TOTAL NUMBER SENSORS	4	33500.00	132.90	4055.20	9016.00
	RESTRICTIONS		50000.00	400.00	6500.00	10000.00

HIT CARRIAGE RETURN TO CONTINUE !

*** SENSOR CANDIDATE SET # 10 ***

MEASUREMENT	MEASUREMENT ACCURACY NEEDED	SENSOR ACCURACY	MEASUREMENT RELIABILITY NEEDED	SENSOR RELIABILITY
AIRSPEED (KNOTS)	15.0000	1.0000	0.9800	0.9972
ALTITUDE (FEET)	50.0000	10.0000	0.9800	0.9972
AZIMUTH (MRAD)	1.7000	1.5000	0.9900	0.9993
ELEVATION (MRAD)	3.2000	3.0000	0.9900	0.9993
RANGE (FEET)	16.0000	15.0000	0.9900	0.9993
ROLL RATE (DEG/HR)	0.0800	0.0100	0.9980	0.9986
PITCH RATE (DEG/HR)	0.0800	0.0100	0.9980	0.9986
YAW RATE (DEG/HR)	0.0800	0.0100	0.9980	0.9986
LONG ACCN (MG)	0.0170	0.0100	0.9900	0.9972
LATE ACCN (MG)	0.0170	0.0100	0.9900	0.9972
VERT ACCN (MG)	0.0170	0.0100	0.9900	0.9972

DO YOU WANT PERFORMANCE OF THIS SENSOR SET ?Y

*** SENSOR CANDIDATE SET # 10 ***

RELEASE ALTITUDE (FT)	=	5000.00
AIRSPEED (FPS)	=	844.50
SLANT RANGE AT RELEASE (FT)	=	7071.07
TIME OF FALL (SEC)	=	24.92
TERMINAL IMPACT ANGLE (DEG)	=	45.00
ALTITUDE ERROR (FT)	=	10.0000
VERTICAL VELOCITY ERROR (FPS)	=	0.0250
LATERAL VELOCITY ERROR (FPS)	=	1.1003
AIRSPEED ERROR (FPS)	=	1.1003
ROLL ANGLE ERROR (MRAD)	=	0.0431
PITCH ANGLE ERROR (MRAD)	=	0.0432
YAW ANGLE ERROR (MRAD)	=	0.0690
SLANT RANGE ERROR (FT)	=	15.0000
DEPRESSION ANGLE ERROR (MRAD)	=	3.0000
AZIMUTH ANGLE ERROR (MRAD)	=	1.5000
BALLISTIC ERROR (MRAD)	=	6.0000
WIND ERROR (FPS)	=	1.0000
TIMING ERROR AT RELEASE (SEC)	=	0.1000
NAVIGATION TRACK SIGMA (FT)	=	620.78
NAVIGATION CROSS-TRACK SIGMA (FT)	=	620.43
RANGE SIGMA (FT)	=	119.75
CROSS-RANGE SIGMA (FT)	=	56.83
WEAPON DELIVERY CEP (FT)	=	156.07
MEAN EFFECTIVE RADIUS OF WEAPON (FT)	=	163.38

PROBABILITY OF ACQUISITION=0.9533
PROBABILITY OF KILL GIVEN ACQUISITION=0.8242
COMPUTED PROBABILITY OF KILL=0.7857

SELECT SENSOR CANDIDATE SET ?22

*** SENSOR CANDIDATE SET # 22 ***

NO	SENSOR DESCRIPTION	MULT	COST	WEIGHT	VOLUME	POWER
2	CAPACITIVE PRESSURE TRANS ROSEMOUNT	1	1000.00	0.90	12.00	5.00
5	SOLID STATE SEARCH RADAR TEXAS INSTRUMENTS AN/APQ-122	1	40000.00	200.00	6000.00	5000.00
10	FIBER OPTIC LASER GYRO HONEYWELL	1	7000.00	0.50	3.20	1.00
13	FLOATED PEND ACC HONEYWELL GG177	1	5500.00	1.50	40.00	10.00
	TOTAL NUMBER SENSORS	4	53500.00	202.90	6055.20	5016.00
	RESTRICTIONS		50000.00	400.00	6500.00	10000.00

HIT CARRIAGE RETURN TO CONTINUE !

*** SENSOR CANDIDATE SET # 22 ***

MEASUREMENT	MEASUREMENT ACCURACY NEEDED	SENSOR ACCURACY	MEASUREMENT RELIABILITY NEEDED	SENSOR RELIABILITY
AIRSPEED (KNOTS)	15.0000	1.0000	0.9800	0.9972
ALTITUDE (FEET)	50.0000	10.0000	0.9800	0.9972
AZIMUTH (MRAD)	1.7000	1.0000	0.9900	0.9997
ELEVATION (MRAD)	3.2000	2.0000	0.9900	0.9997
RANGE (FEET)	16.0000	10.0000	0.9900	0.9997
ROLL RATE (DEG/HR)	0.0800	0.0100	0.9980	0.9986
PITCH RATE (DEG/HR)	0.0800	0.0100	0.9980	0.9986
YAW RATE (DEG/HR)	0.0800	0.0100	0.9980	0.9986
LONG ACCN (MG)	0.0170	0.0100	0.9900	0.9972
LATE ACCN (MG)	0.0170	0.0100	0.9900	0.9972
VERT ACCN (MG)	0.0170	0.0100	0.9900	0.9972

DO YOU WANT PERFORMANCE OF THIS SENSOR SET ?Y

*** SENSOR CANDIDATE SET # 22 ***

RELEASE ALTITUDE (FT)	=	5000.00
AIRSPEED (FPS)	=	844.50
SLANT RANGE AT RELEASE (FT)	=	7071.07
TIME OF FALL (SEC)	=	24.92
TERMINAL IMPACT ANGLE (DEG)	=	45.00
ALTITUDE ERROR (FT)	=	10.0000
VERTICAL VELOCITY ERROR (FPS)	=	0.0250
LATERAL VELOCITY ERROR (FPS)	=	1.1003
AIRSPEED ERROR (FPS)	=	1.1003
ROLL ANGLE ERROR (MRAD)	=	0.0431
PITCH ANGLE ERROR (MRAD)	=	0.0432
YAW ANGLE ERROR (MRAD)	=	0.0690
SLANT RANGE ERROR (FT)	=	10.0000
DEPRESSION ANGLE ERROR (MRAD)	=	2.0000
AZIMUTH ANGLE ERROR (MRAD)	=	1.0000
BALLISTIC ERROR (MRAD)	=	6.0000
WIND ERROR (FPS)	=	1.0000
TIMING ERROR AT RELEASE (SEC)	=	0.1000
NAVIGATION TRACK SIGMA (FT)	=	620.78
NAVIGATION CROSS-TRACK SIGMA (FT)	=	620.43
RANGE SIGMA (FT)	=	116.58
CROSS-RANGE SIGMA (FT)	=	56.55
WEAPON DELIVERY CEP (FT)	=	152.56
MEAN EFFECTIVE RADIUS OF WEAPON (FT)	=	163.38

PROBABILITY OF ACQUISITION=0.9533
PROBABILITY OF KILL GIVEN ACQUISITION=0.8357
COMPUTED PROBABILITY OF KILL=0.7967

SELECT SENSOR CANDIDATE SET ?0

APPENDIX D

EXAMPLES OF COMPUTERIZED LITERATURE SEARCH

Example 1: Descriptor: aircraft control systems integration
(143 items)

The Impact of Integrated Guidance and Control Technology on Weapons Systems Design

Advisory Group for Aerospace Research and Development Neuilly-Sur-Seine (France) (400043)

Conference proceedings.
F1234C4 Fld: 1C, 17G, 19E, 5H, 1D, 51C, 79F, 51E GRAI7915
Dec 78 244p
Rept No: AGARD-CP-257
Monitor: 18
Presented at the Guidance and control Panel Symposium, 9-12 May 78, Sandefjord, Norway. _See also Supplement, AD-C016 896._

Abstract: The rapidly developing technologies in navigation, sensors, target identification sensors, command and control and computation capability are structuring a command network that demands increased functional integration of crew station and control configuration to permit effective use of that technology. This technology, when combined with advancing technologies in guidance and control, the driving forces of acquisition and life cycle costs, needs for operational tactical flexibility, survivability, vulnerability, and critical volume and weight constraints, dictates the need for integrated guidance and control at a higher functional level than heretofore considered. This higher functional level involves an effective blend of the sensor, vehicle and kill-mechanism that can provide a multi-role capability for advanced and present operational vehicles. The papers presented herein definitely indicate that when one considers the large array of sensors available and the fundamental commonality of functions and control algorithms for different missions, it appears logical that these capabilities should be utilized to augment each other to achieve flexibility and growth capability.

Descriptors: *Flight control systems, *Aircraft fire control systems, *Command and control systems, *Weapon delivery, Navigational aids, Integrated systems, Global positioning system, Guidance, Man machine systems, Display systems, Pilots, Flight crews, Cockpits, Avionics, Flight simulators, Data processing

Identifiers: NATO furnished, C3(Command control and communications), NTISDODXA, NTISFNFN

AD-A065 928/4ST NTIS Prices: PC A11/MF A01

An Integrated Fault-Tolerant Avionics System Concept for Advanced Aircraft

Charles Stark Draper Lab., Inc., Cambridge, MA. (408386)

Final rept.
F1155K1 Fld: 1D, 1C, 51E, 51C GRAI7914
1 Feb 79 325p
Rept No: R-1226
Contract: N00019-78-C-0572
Monitor: 18

Abstract: A conceptual baseline design for a highly integrated fault- and damage-tolerant avionics architecture is presented. The architecture is generic in nature, and applicable to a broad range of aircraft types: including CTOL, VTOL, and V/STOL; and all classes from supersonic fighters to transports. The architecture embodies pools of modular resources, configured to flexibly serve required functions on a priority basis. By including system elements which can serve multiple functions and taking maximum advantage of systematic fault-tolerance methods and procedures, the design tends to minimize replication of elements and overall complexity. In concert with logistics and maintenance procedures designed around the pooled modular element approach, the architecture can provide required performance, reliability, damage tolerance, and availability at minimum life-cycle costs. Its inherent flexibility allows it to readily incorporate a wide variety of mission-specific elements and to easily adapt to growth and change as new elements and requirements arise. (Author)

Descriptors: *Naval aircraft, *Avionics, Jet fighters, Transport aircraft, Vertical takeoff aircraft, Short takeoff aircraft, Helicopters, Flight control systems, Navigation, Display systems, Communication equipment, Fault tolerant computing, Integrated systems, Military applications, Maintainability, Modular construction, Life cycle costs

Identifiers: NTISDODXA

AD-A065 136/4ST NTIS Prices: PC A14/MF A01

Flight Evaluation MK II Integrated Controller Installed in an OH-58A Helicopter

Army Aviation Engineering Flight Activity, Edwards AFB, CA. (409025)

Final rept.
AUTHOR: Hagen, John F.; Moe, Patrick J.; Woratschek, Ralph
F1154G1 Fld: 1D, 1B, 5E, 51E, 51B, 95D GRAI7914
Apr 78 66p
Rept No: USAAEFA-77-11
Monitor: 18

Abstract: This Activity conducted a limited handling qualities and pilot workload evaluation of the MK II integrated controller installed in an OH-58A helicopter. The evaluation consisted of 22 flights for 15.2 hours of productive flight test time. The OH-58A could be safely flown throughout the recommended flight envelope using the integrated controller. The pilot workload when using the integrated controller with two hands was not reduced from and was sometimes greater than the workload when using conventional controls for all maneuvers except level forward flight. Single hand control during flight and landing could be safely accomplished, but required increased pilot workload in all cases. The two most serious unsatisfactory characteristics identified were lack of an adequate system-decoupled warning and excessive workload during left sideward flight between approximately 15 to 25 knots true airspeed. Three unsatisfactory characteristics that contributed to the increased workload when using the integrated controller were excessive longitudinal and lateral integrated controller response and sensitivity, lack of control displacement harmony between the integrated controller cyclic and collective controls, and inadvertent cyclic control inputs with collective control movement. The reduced longitudinal and lateral control authority, which limited the aircraft's forward flight capability at aft center of gravity, rearward flight capability at forward center of gravity, and slope landing capability, was also an unsatisfactory characteristic. Eight additional unsatisfactory characteristics were also identified.

Descriptors: *Flight control systems, Helicopters, Flight testing, Pilots, Man machine systems, Handling, Flight maneuvers, Job analysis, Aircraft landings, Turning flight, Integrated systems, Manual operation, Decoupling(Interaction), Roll, Pitch(Motion)

Identifiers: Workloads(Human), H-58 helicopters, OH-58A helicopters, Mark-2 integrated controllers, NTISDODXA

AD-A065 072/1ST NTIS Prices: PC A04/MF A01

Active Controls in Aircraft Design

Advisory Group for Aerospace Research and Development, Neuilly-sur-Seine (France). (400043)
AUTHOR: Kurzhals, P. R.
F0922G4 Fld: 1D, 1C, 51E, 51C GRAI7912
Nov 78 180p
Rept No: AGARD-AG-234
Monitor: 18

Abstract: Active controls offer the promise of significantly increased aircraft performance and operational capability. However, realization of these gains will require major changes in both the aircraft design approach and in the implementation of the flight control system. This AGARDograph addresses related control-configured vehicle design and system considerations summarizes representative applications of active control for fighter and transport aircraft. This AGARDograph was prepared at the request of the Guidance and Control Panel of AGARD.

Descriptors: *Aircraft, *Fly by wire control, *Maneuverability, Efficiency, Weight reduction, Aerodynamic characteristics, Operation, Costs, Integrated systems, Flight control systems, Propulsion systems, Jet fighters, Jet transport planes, Jet bombers, Transport aircraft, Remotely piloted vehicles, Fuels, Conservation

Identifiers: NATO furnished, *Control configured vehicles, B-1 aircraft, F-16 aircraft, F-8 aircraft, C-5A aircraft, PROFIT(Propulsion Flight Control Integration Technology), Commercial aircraft, Military aircraft, Technology, NTISDODXA

AD-A063 793/4ST NTIS Prices: PC A09/MF A01

Integration of Air Cushion Landing System Technology into the JINDIVIK Remotely Piloted Vehicle

Boeing Aerospace Co Seattle Wash (059610)

Final rept. Apr 75-Jan 77
AUTHOR: Lloyd, A. J. P.; McAvoy, J. J.; Rajpaul, V. K.
E2543K4 Fld: 1C, 1B, 51C, 51B GRAI7824
Mar 78 310p
Contract: F33615-75-C-3088
Project: 2402
Task: 01
Monitor: AFFDL-TR-77-21

Abstract: Studies have been conducted on an Air Cushion Landing System for the Australian Jindivik target drone aircraft. Analyses are presented of the airflow and yaw thruster control systems, and the vehicle stability with a deployed recovery trunk is assessed. The vehicle touchdown and slideout on a recovery trunk are presented, and the design of an improved retention/release system is shown. (Author)

Descriptors: *Remotely piloted vehicles, *Air cushion vehicles, *Aircraft landings, Integrated systems, Cushioning, Soft landings, Recovery, Yaw, Aerodynamic characteristics, Target drones, Thrust vector control systems, Australia, Foreign technology

Identifiers: JINDIVIK remotely piloted vehicle, NTISDODXA

AD-A058 004/3ST NTIS Prices: PC A14/MF A01

Engineering and Development Program Plan Advanced Integrated Flight Systems (AIFS)

Federal Aviation Administration Washington D C Systems Research and Development Service (340170)

Rept. for period ending Mar 78.
E2292F1 Fld: 1C, 1D, 85A, 51C, 51E GRAI7822
Mar 78 84p
Rept No: FAA-ED-18-3
Monitor: 18

Abstract: It appears that active controls and digital flight control and avionics will significantly impact transport aircraft technology, and therefore, FAA must examine the impact of these advances on airworthiness criteria. To comply with its charged responsibilities, the FAA must stay abreast of technology advancements and establish the necessary safety standards. In the areas of active controls technology and digital flight control and avionics, a technology program entitled 'Advanced Integrated Flight Systems' (AIFS) has been established to support this responsibility. The AIFS Technology Program will provide for the acquisition or development of the generic data base from which the Flight Standards Service may develop airworthiness criteria and compliance procedures for aircraft and equipment evolving from the application of advanced integrated flight systems technology.

Descriptors: *Flight control systems, *Jet transport planes, Commercial aircraft, Digital systems, Avionics, Airworthiness, Aviation safety, Standards, Integrated systems, Data bases

Identifiers: NTISDODXA, NTISDOTFAA

AD-A058 770/1ST NTIS Prices: PC A05/MF A01

Specifications for IDAMST Software. (Mission Analysis)

Boeing Aerospace Co Seattle Wa Boeing Military Airplane Development (410258)

Final rept. Apr-Jun 76
AUTHOR: Tubb, David G.
E2054H1 Fld: 9B, 1C, 14B, 51E GRAI7820
Jul 77 169p
Contract: F33615-76-C-1099
Project: 2003
Task: 01
Monitor: AFAL-TR-76-208-VOL-2
See also Volume 1, AD-A047 163.
Availability: Microfiche copies only.

Abstract: The objective of this program was to define the operational flight program and the operational test program for an Integrated Digital Avionics System (DAIS) for the Medium STOL (IDAMST) airplane. This effort is part of an Air Force Avionic Laboratory Program to specify a candidate avionics design based on DAIS technology. The approach involved the development of software requirements derived from the system analysis of the hardware baseline and the operational analysis of the AMST mission. The software requirements were developed into a specific IDAMST software design. The design is described in terms of functional, architectural, and configurational characteristics. The design documents consist of four Computer Program Development Specifications, Type B5 per MIL-STD-490 and MIL-STD-483. The IDAMST software design was based on DAIS architecture and adapted as required to meet the IDAMST requirements. The DAIS architecture proved to be flexible allowing the design to be extended to IDAMST without major change. The IDAMST system defined satisfies the functional and operational requirements of the AMST. The design consists of a dual redundant processor with a reprogrammable backup processor. (Author)

Descriptors: *Computer programming, *Avionics, Transport aircraft, Missions, Short takeoff aircraft, Air drop operations, Military requirements, Systems analysis, Integrated systems, Digital systems, Computer architecture, Flight control systems, Display systems, Flight paths, Redundant components, Specifications

Identifiers: IDAMST system, C-14 aircraft, NTISDODXA

AD-A055 940/1ST NTIS Prices: MF A01

HHSD Demonstration Model Development

RCA Government and Commercial Systems Burlington Ma Automated Systems Div (409516)

Final rept. Sep 76-Dec 77
AUTHOR: Burton, G. T.; Clay, B. R.
E1695C1 Fld: 1D, 1C, 51E, 51C GRAI7817
Dec 77 63p
Contract: N62269-76-C-0390
Monitor: 18

Abstract: This Final Report summarizes the status of the Holographic Horizontal Situation Display effort. This program's objective was the development and optimization of the techniques and hardware required to demonstrate a bright, high contrast, annotatable, multicolor display. Display hardware with a CRT, tape transport and source tapes were developed that demonstrate the characteristics of the focussed image holographic storage technique as applied to the annotated moving map display requirement of the HHSD application of the AIDS program. (Author)

Descriptors: *Display systems, *Holography, *Aircraft equipment, Cockpits, Control panels, Cathode ray tubes, Colors, Tape recorders, Image processing, Storage, Maps, Registers(Circuits), Addressing

Identifiers: HSD(Horizontal situation display), AIDS(Advanced integrated display system), Horizontal situation display, Advanced integrated display system, NTISDODXA

AD-A054 437/9ST NTIS Prices: PC A04/MF A01

Avionics Processor-Controller Configuration Study. Volume I. Technical Report

Autonetics Anaheim Calif (048 100)

Final rept. 1 Jul 72-30 Jun 73
AUTHOR: Koczela, L. J.
E1191C1 Fld: 9B, 19E, 1C GRAI7813
30 Jun 73 237p
Rept No: C72-812/201-Vol-1
Contract: F33615-72-C-1973
Project: AF-6090
Task: 609001
Monitor: AFAL-TR-73-203-Vol-1
See also Volume 2, AD-911 356L.
Distribution limitation now removed.

Abstract: This report presents the results of a study to configure an advanced multiprocessor for an avionics system. An advanced strategic bomber avionics system was selected as representative of an advanced avionics system application and computational requirements for this system were defined. The prototype laboratory version of an advanced multiprocessor developed by Burroughs Corporation under Air Force Avionics Laboratory sponsorship was examined and applied to the avionics system. It was found that the Burroughs multiprocessor offers a very flexible and adaptable design. Several improvements were noted to improve its performance and several design modifications were noted which are required in order to apply the design to the avionics system. The resultant configuration showed that mechanization of the computer system, using state-of-the-art technology, for an advanced strategic bomber avionics system is feasible with the Burroughs multiprocessor concept. This report is also being published as Autonetics internal report C72-812/201. (Author)

Descriptors: (*Data processing, *Strategic bombing), (*Fire control computers, Strategic bombing), (*Aircraft fire control systems, *Jet bombers), Airborne, Electronic equipment, Digital computers, Programming languages, Multiplexing, Integrated systems, Navigation, Target acquisition, Penetration aids, Memory devices, Data storage systems, Data transmission systems, Advanced weapons, Switching circuits, Interfaces

Identifiers: *Avionics, *B-1 aircraft, Computer architecture, *Delivery tactics, Microprogramming, *Multiprocessing, NTISDODXD

AD-911 355/6ST NTIS Prices: PC A11/MF A01

Test and Development of Flight Control Actuation System Components for Military Aircraft

Hydraulic Research and Mfg Co Valencia Calif (389 037)

Final rept. 8 Dec 70-3 Nov 71
AUTHOR: Goldstein, Sanford M.; Schreadley, Harry W.; Bazill, Dale G.
E1005D1 Fld: 1C, 13G, 9E GRAI7811
Feb 72 230p
Contract: F33615-71-C-1124
Project: AF-8225
Task: 822510
Monitor: AFFDL-TR-72-13
Distribution limitation now removed.

Abstract: Test and development activities were conducted in the following nine areas: (1) Evaluation of a breadboard multiplexing system driving a fly-by-wire actuator; (2) Evaluate actuation system of six-degree of freedom motion base; (3) Evaluation of general purpose actuator test stand;; (4) Various design concepts were explored for the improvement of branch isolation techniques; (5) Evaluation of a Vickers Inc. integrated servopump actuator package; (6) Investigation of limit cycle characteristics of a General Electric 666A actuator; (7) Literature search and recommendation for a laboratory contamination measurement system choice; (8) Fabrication of a portable flow measurement stand and (9) Design and fabrication of a transducer range and balance panel.

Descriptors: (*Flight control systems, *Actuators), Fly by wire control, Hydraulic actuators, Degrees of freedom, Servomechanisms, Hydraulic fluids, Contamination, Multiplexing, Signals, Integrated systems, Analog to digital converters, Timing devices, Digital computers, Noise(Electrical and electromagnetic), Servovalves, Hydraulic servomechanisms, Redundant components, Computer programs, Breadboard models, Flight simulators, Electrohydraulic valves, Leakage(Fluid), Hydraulic test units, Jet fighters, Military aircraft, Test methods, Test stands

Identifiers: Spider leg actuators, F-4 aircraft, NTISDODXD

AD-918 237/9ST NTIS Prices: PC A11/MF A01

Example 2: Descriptor: aircraft sensor integration
(8 items)

Print 9/5/1-8
DIALOG File6: NTIS 64-79/ISS19 (Copr. NTIS) (Item 1 of 8) User5422 6sep79

Development of Feasibility Demonstration Hardware for an Integrated Fire and Overheat Detection System

Air Force Aero Propulsion Lab Wright-Patterson AFB Ohio (011570)

Final rept. Jun 70-Dec 71
AUTHOR: Fox, Duane G.
C1242G2 Fld: 1C, 13L, 85D*, 51G GRA17316
May 73 40p*
Rept No: AFAPL-TR-72-105
Project: AF-3048
Task: 304807
Monitor: 18

Abstract: The report summarizes the results of an in-house effort to develop and demonstrate the feasibility of an integrated fire and overheat detection system for an aircraft engine nacelle. The integrated system was conceived in 1965 as a means of decreasing the number of nondetected engine nacelle fires and the incidence of false fire warnings on operational Air Force aircraft. Analysis of the reported engine nacelle fires and fire warnings shows that approximately 50% of the fires were not detected by the fire or overheat detection system during the six-year period 1965-1970, and 83% of the fire and overheat warnings were false. Two integrated systems were developed to demonstrate total system feasibility, and these systems were further evaluated on flight test aircraft. The report presents the results of this evaluation. (Modified author abstract)

Descriptors: (*Aircraft fires, Detection), (*Jet engine nacelles, Aircraft fires), Sensors, Infrared detectors, Ultraviolet detectors, Turbojet engines, Integrated circuits, Flight testing

Identifiers: *Aircraft fire detection systems, *Engine overheating, AF

AD-762 919 NTIS Prices: PC A03/MF A01

Survivable Flight Control System. Studies, Analyses and Approach. Supplement for Control Criteria Studies

Mcdonnell Aircraft Co St Louis Mo (403111)

Interim rept. no. 1, Jul 69-May 71
AUTHOR: Kisslinger, Robert L.; Wendl, Michael J.
A2883H3 Fld: 1C, 51B GRA17116
May 71 194p
Contract: F33615-69-C-1827
Project: AF-680J
Monitor: AFFDL-TR-71-20-Suppl-1

See also Supplement 3, AD-727 763.

Abstract: The Survival Flight Control System (SFCS) Program is an advanced development program of which the principal objective is the development and flight test demonstration of an SFCS utilizing fly-by-wire and integrated actuator package techniques. The studies and analyses conducted to date have sufficiently defined the system requirements to provide a definition of an approach to the implementation of the SFCS. The results of these studies and the definition of the approach are presented in the basic report. Details of the Control Law Development, and Hydraulic Power Actuation studies are presented in report supplements 2 and 3, respectively. The results of the Control Criteria studies are presented in this supplement. (Author)

Descriptors: (*Jet fighters, *Flight control systems), Vulnerability, Sensors, Servomechanisms, Integrated circuits, Flight simulators, Pilots Air Force training, Programming(Computers)

Identifiers: *Fly by wire control systems, SFCS(Survivable Flight Control Systems), Survivable flight control systems, F-4 aircraft, Avionics, *Man in the loop control systems

AD-727 762 NTIS Prices: PC A09/MF A01

A COMMENTARY UPON AIRCRAFT NAVIGATION SYSTEMS

Royal Aircraft Establishment Farnborough (England) (310450)

Technical rept.
AUTHOR: Carr, J. G.; Stringer, F. S.
A0595L3 Fld: 17G, 76D, 76C USGRDR7017
Oct 69 25p
Rept No: RAE-TR-69220
Monitor: TRC-BR-19285

Abstract: Navigational accuracy and reliability requirements for civil air transports are becoming progressively more stringent for both the en-route and terminal area phases of flight and the specification of the navigation aids and systems used must be constantly reviewed. The paper briefly surveys the status of navigation aids today, pointing out the advantages and disadvantages of individual aids and concluding that a hybrid system, combining two or more dissimilar aids or sensors is desirable. The methods of achieving such a hybrid are discussed. The paper details some of the significant design features and performance characteristics peculiar to the radio sensors which are considered for possible inclusion in the hybrid, and stresses the important part that digital management computers and CRT displays can play in integrated navigation systems. (AUTHOR)

Descriptors: (*Navigation, Aircraft), Reviews, Navigational aids, Sensors, Radio equipment, Navigation computers, Display systems, Integrated systems, Great Britain

AD-708 618 CFSTI Prices: HC A02/MF A01

HYBRID NAVIGATION SYSTEMS

Advisory Group for Aerospace Research and Development Paris (France) (400043)

Conference proceedings
AUTHOR: Warner, G. R.; Leonard, B. P.; Mitchell, M. W.; Stringer, F. S.; Pearson, M. G.
7395F4 Fld: 17G, 926 USGRDR7008
Jan 70 320p*
Rept No: AGARD-CP-54
NATO furnished. Presented at the Guidance and Control Panel Meeting (9th), Delft (Netherlands), 22-26 Sep 69.

Abstract: Contents: Hybrid guidance and navigation systems; Characteristics of a satellite navigation system operated in conjunction with a user inertial system; Global navigation/traffic surveillance/communication satellite system for military and civil vehicles; The TMA role of hybrid system radio sensors; The use of filtering techniques and/or mixed navigation systems in combination with barometric altimetry to generate glide slopes for precision approach; The use of inertial information to improve automatic ILS approach performance; Improvement of the accuracy of automatic landing systems by use of Kalman-filtering techniques and incorporation of inertial data; Collision avoidance and the air traffic control environment; Integrated hybrid-inertial aircraft navigation systems; Modern aircraft navigation sensors for hybrid systems; Loran systems technology; Systeme de navigation a inertie hybride optimise; Tactical loran; The C-5 navigation system - an application of digital synergistic stochastic hybrid navigation technology; The hybrid navigation system for the nimrod maritime patrol aircraft; The use of hybrid techniques in commercial transport aircraft; Integrated avionic system design for helicopters and VTOL; Integrated navigation by least square adjustment; A simple Kalman filter for VOR/DME; Optimal correction of stochastic errors of inertial systems; Design of low sensitivity Kalman filters for hybrid navigation systems.

Descriptors: (*Navigation, Symposia), Guidance, Control systems, Integrated systems, Air traffic control systems, Aircraft, Sensors, Radio navigation, Inertial navigation, Navigation satellites, Reviews

Identifiers: Hybrid navigation systems

AD-701 775 CFSTI Prices: HC A14/MF A01

DESIGNING DIFFERENTIATING AND INTEGRATING GYROSCOPES AND ACCELEROMETERS

Foreign Technology Div Wright-Patterson AFB Ohio (141600)
AUTHOR: Nikitin, E. A.; Balashova, A. A.
7313J3 Fld: 17G, 926 USGRDR7007
21 Oct 69 268p
Rept No: FTD-MT-24-200-69
Project: FTD-60502
Edited machine trans. of mono. Porektirovanie Differentsiruyushchikh i Integriruyushchikh Giroskopov i Akselerometrov, Moscow, 1969 p1-216.

Abstract: The book covers the fundamentals of analysis and designing of differentiating and integrating gyroscopes and accelerometers and an analysis of their errors under different operating conditions is given. Simple calculation formulas for determination of the basic parameters of these instruments and also their instrumental and methodical errors are given. Depending upon the assignment of the instrument, requirements for static, dynamic, and accuracy characteristics are shown. Much attention is given description of the physical essence and causes of appearance of the examined errors. (Author)

Descriptors: (*Accelerometers, Design), (*Attitude control systems, Inertial guidance), (*Gyroscopes, Design), Aircraft, Guided missiles, Equations of motion, Gyro stabilizers, Sensors, Textbooks, USSR

Identifiers: Translations

AD-700 605 CFSTI Prices: HC A12/MF A01

INTEGRATED FIRE AND OVERHEAT DETECTION SYSTEM FOR AIRCRAFT

General Motors Corp Kokomo Ind Delco Radio Div (107900)

Technical rept. 15 Nov 68-15 Sep 69
AUTHOR: Raskauskas, Bernard J.
7175A1 Fld: 13L, 1C, 941, 902 USGRDR7005
Dec 69 72p*
Contract: F33615-69-C-1196
Project: AF-3048
Monitor: AFAPL-TR-69-97

Abstract: The object of the program was to design and build an operational fire and overheat detection system, which used continuous sensors, PIN sensors, silicon solar cell sensors, and silicon carbide sensors for manned flight vehicles. The system consists of sensitizing modules, detection circuits and logic circuits. Operational capability ranges from -55C to +125C. The system is designed to drive a readout with four separate notations, FIRE, OVERHEAT, FAIL and OK. (Author)

Descriptors: (*Fire alarm systems, Aircraft equipment), (*Temperature warning systems, Aircraft equipment), Aircraft engines, Sensors, Temperature sensitive elements, Photodiodes, Solar cells, Silicon, Silicon carbides, Diodes(Semiconductor), Integrated circuits, Logic circuits, Modules(Electronics)

Identifiers: Overheating

AD-699 210 CFSTI Prices: HC A04/MF A01

APPLICATION OF AIRCRAFT INTEGRATED DATA SYSTEMS

Advisory Group for Aerospace Research and Development Paris (France) (400043)
AUTHOR: den Hartog, C.
5121L1 Fld: 1C USGRDR6822
Dec 67 109p
Rept No: AGARD-561
NATO Furnished.

Abstract: The subject was interpreted broadly to include all aspects of data acquisition, and to be synonymous with the term Aircraft Integrated Data Systems (AIDS). The processed data can be analysed and used in accident investigation, project design, airworthiness (including fatigue) studies, aircraft maintenance and mission performance assessment; a review is given of past activities, current requirements and future development in these fields. In the first three of these areas procedures are well-established and relatively simple instrumentation is available; in mission performance assessment and aircraft maintenance, however, AIDS have reached a less advanced stage, though great promise is shown. In general, it is concluded that, although a considerable range of techniques and equipment already exists, most are of an experimental nature and it is essential that equipment suppliers should continue to strive to reduce size, weight and cost while improving accuracy and reliability. (Author)

Descriptors: (*Aircraft equipment, *Warning systems), Malfunctions, Sensors, Recording systems, Maintenance, Reliability, Aviation accidents, Data processing systems, Aviation safety

Identifiers: *AIDS(Aircraft Integrated Data System), *Aircraft integrated data systems

AD-674 978 CFSTI Prices: PC A06/MF A01

THE AIRCRAFT INTEGRATED DATA SYSTEM, ACIDS

Parks Coll of Aeronautical Technology East St Louis Ill (403689)

Final rept.
AUTHOR: Harrington, J. F.; Bryer, J. W.; George, J. A.; Shank, R. R.; Carter, D. W.
4654J2 Fld: 1C, 14D, 9E USGRDR6814
Jun 68 246p*
Contract: DAAJ01-67-C-0733
Project: DA-1F121401A43405
Monitor: USAAVCOM-TR-68-1

Abstract: The report constitutes a systems engineering study for the design of a system which can, by means of a tape recording of the history of performance and condition of respective dynamic components, make deterministic predictions of the operational life of the components so measured and provide a capability for detection and diagnosis of malfunctions. In addition, the system will provide data for prediction of on-condition removal, for fleet analysis, for determination of usage rates, and data which should be used as the predicate for the prediction of future parts and spares requirements. The study includes consideration of the parameters to be monitored, the hardware concept to implement the system, the mathematical models for data analysis, the software requirements, and the management aspects. The primary finding made is that the proposed system (ACIDS) for the UH-1D is feasible, practical, and economical. (Author)

Descriptors: (*Helicopters, *Warning systems), Malfunctions, Sensors, Recording systems, Maintenance, Data processing systems, Automatic, Systems engineering, Cost effectiveness, Feasibility studies, Identification systems, Commercial planes, Magnetic tape

Identifiers: UH-1D aircraft, H-1 aircraft, ACIDS(Aircraft Integrated Data System), Aircraft integrated data systems

AD-669 282 CFSTI Prices: PC A11/MF A01