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AFFDL-TR-75-59

DEFINITION STUDY FOR AN ADVANCED FIGHTER DIGITAL FLIGHT CONTROL SYSTEM

MCDONNELL AIRCRAFT COMPANY
MCDONNELL DOUGLAS CORPORATION
Saint Louis, Missouri 63166

June 1975
Technical Report AFFDL-TR-75-59
Final Report for Period March 1974 - May 1975

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Prepared for
Air Force Flight Dynamics Laboratory
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Wright-Patterson AFB, Ohio 45433

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Digital Flight Control Systems
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Digital System Synthesis
Displays
Flight Control
Flight Management
Fly-By-Wire
Handling Qualities

20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

The Definition Study for an Advanced Fighter Digital Flight Control System is an exploratory definition study of which a principal objective is to derive and evaluate custom multimode control laws, related displays, and multichannel digital fly-by-wire implementation schemes for advanced Air Force and Navy fighters. → continued 1473B

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In-line Monitoring
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Redundancy Management
Redundant Systems
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20. ABSTRACT (Continued)

A summary of the analytical studies performed and the results of analyses are given. A description of the simulations and evaluations conducted is provided. A recommended configuration for an advanced development program is presented. Also described is the support provided by four companies under subcontract to MCAIR: Collins Avionics Division, General Electric Co., Honeywell, and Lear Siegler, Inc.

from 1473A

Study results show that a triplex flight control system provides the lowest weight, the best maintainability, and the lowest cost of the candidate configurations considered. Results also indicate that mission-oriented flight control laws integrated with compatible displays and controllers can provide enhanced mission effectiveness and reduced pilot workload.

It is recommended that the concepts analyzed and simulated during this definition study be implemented and evaluated by flight testing.

1473B

FOREWORD

This report was prepared by McDonnell Aircraft Company, St. Louis, Missouri, under Air Force Contract F33615-74-C-3047, the Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio. The program was jointly directed by the Air Force and Navy. The Air Force program manager was Mr. W. G. James, AFFDL, Flight Control Division, Wright-Patterson Air Force Base, Ohio; the Navy deputy program manager was Mr. C. R. Abrams, Naval Air Development Center, Warminster, Pennsylvania. In addition, evaluation pilots and technical support personnel were provided by the Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio; Air Force Flight Test Center, Edwards AFB, California; Kirtland AFB, New Mexico; Naval Air Station (VF-124), Miramar, California; Naval Air Test Center, Patuxent River, Maryland; and Randolph AFB, Texas.

This report covers work performed between March 1974 and May 1975.

Principal contributors to this report are the MCAIR Digital FCS project personnel of many disciplines under the direction of David S. Hooker, Project Engineer; Ira G. Pope, Senior Project Electronics Engineer; George R. Smith, Project Electronics Engineer; and George J. Vetsch, Senior Group Engineer - Guidance and Control Mechanics.

The authors wish to acknowledge the contributions of the MCAIR Digital Fly-by-Wire (FBW) project personnel for the content reported herein. Acknowledgement also is given to project personnel of the following subcontractors for contributions to this program:

- Collins, Cedar Rapids, Iowa
- General Electric, Binghamton, New York
- Honeywell, Minneapolis, Minnesota
- Lear Siegler, Santa Monica, California

This report was submitted by the authors in May, 1975.

This technical report has been reviewed and is approved.

FOR THE COMMANDER

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LIST OF ABBREVIATIONS, ACRONYMNS, AND SYMBOLS

ABBREVIATIONS AND ACRONYMS:

AAA - Anti Aircraft Artillery
A/A, AA - Air-to-Air
A - Amperes
AACM - Air-to-Air Combat Mode, MCAIR Developed
A/B - Afterburner
A/C - Aircraft
AC - Alternating Current
ACL - Automatic Carrier Landing
ACLS - Automatic Carrier Landing System
ACM - Air Combat Mode, G.E. Developed
A/D - Analog to Digital
ADI - Attitude - Director Indicator
ADP - Advanced Development Program
AF - Air Force
AFFDL - Air Force Flight Dynamics Laboratory
A/G - Air-to-Ground
AGE - Aerospace Ground Equipment
AHRS - Attitude-Heading Reference System
AIM - Analog Isolation Mechanism
AIMIS - Advanced Integrated Modular Information System
AOA - Angle-of-Attack
ARI - Aileron Rudder Interconnect
ASE - Allowable Steering Error
ASW-25 - Automatic Landing Data Link Receiver
AUTO - Automatic
BIT - Built-In Test
BKN - Beacon
C - Coulombs
CADC - Central Air Data Computer
CAS - Control Augmentation System
CCV - Control Configured Vehicle
CDC - Computer and Display Controller
CG - Center of Gravity
CPR - Coupler
CPU - Central Processor Unit
CRT - Cathode Ray Tube
D/A - Digital to Analog
DAIS - Digital Avionics Information System
DC - Direct Current
DFCC - Digital Flight Control Computer
DFCS - Digital Flight Control System
DFMS - Digital Flight Management System
DIF - Digital Interface Unit
DigiPACT - Digitized PACT Control Laws
DLC - Direct Lift Control
DMA - Direct Memory Access
DMC - Deck Motion Compensation
DSF - Direct Side Force
EADI - Electronic ADI

EBU - Electrical Backup
EHSI - Electronic HSI
EM - Energy Management
EMC - Electromagnetic Compatibility
EMI - Electromagnetic Interference
EO - Electro-Optical
FAA - Federal Aviation Administration
FBW - Fly-By-Wire
FCS - Flight Control System
FDL - AFFDL
FMEA - Failure Mode and Effect Analysis
FOM - Figure of Merit
FOV - Field of View
FWD - Forward
G.E. - General Electric Co.
GP - General Purpose
GS - Ground Speed
GSE - Ground Support Equipment
HAC - High Acceleration Cockpit
HSI - Horizontal Situation Indicator
HUD - Head-Up Display
IBM - International Business Machines, Inc.
IDIIOM - Information Display Incorporated Input/Output Machine
IFF - Identification - Friend or Foe
IFIM - In Flight Integrity Management
IIPACS - Integrated Information Presentation and Control System
ILS - Instrument Landing System
INS - Inertial Navigation System
I/O - Input/Output
IPS - Inches per Second
IR - Infrared
KA - Kiloamperes
KVA - Kilovolt Amperes
L/D - Lift to Drag Ratio
LRU - Line Replaceable Unit
LVDT - Linear Variable Differential Transformer
MACS - Manned Air Combat Simulator
MAN - Manual
MCAIR - McDonnell Aircraft Company
MCDP - Master Control and Display Panel
MCDT - Mean Corrective Down Time
MCL - Manual Carrier Landing
MFD - Multi-Function Display
MGTF - Mobile Ground Test Facility
MIL - Military
MMH/FH - Maintenance Man Hours per Flight Hour
MMH/OH - Maintenance Man Hours per Operate Hour
MMTR - Mean Man Hours to Repair
MR - Milliradians
MRM - Medium Range Missile
ms - miliseconds
MTBF - Mean Time Between Failures

MTBMA - Mean Time Between Maintenance Action
MTU - Multiplex Terminal Unit
MUX - Multiplex
NAV - Navigation
NM - Nautical Miles
NSS - Neutral Speed Stability
O&M - Operations and Maintenance
ORLA - Optimum Repair Level Analysis
PACT - Precision Aircraft Control Technology
PC1 - Power Control Hydraulic System One
PC2 - Power Control Hydraulic System Two
PR - Pilot Rating
PROM - Programmable Read Only Memory
RDT&E - Research, Development, Test and Evaluation
RF - Radio Frequency
RNAV - Area Navigation
ROM - Read Only Memory
S - Sensor, Controller, Transducer, or Actuator
SAG-FCS - Survivability Assessment Guidelines for Flight Control System
SAM - Surface to Air Missile
SAS - Stability Augmentation System
SFCS - Survivable Flight Control System
SID - Standard Instrument Departure
SIU - Sensor Interface Unit
SL - Sea Level
SLD - Survivability Logic Diagram
SMRD - Spin Motor Rotation Detector
S/N - Serial Number
SOC - Shut Off Command
SOW - Statement of Work
SRM - Short Range Missile
SPN-42 - Shipboard Landing Control System
SSC - Side Stick Controller
SSIU - Subsystem Interface Unit
STAR - Standard Terminal Arrival Route
TAC - Tactical Air Command
TACAN - Tactical Air Navigation
TAS - True Air Speed
T/R - Transformer-Rectifier
TRP - Time Response Parameter
TWeaD - Tactical Weapon Delivery
WRA - Weapons Replaceable Assembly

SYMBOLS:

C^*	Pitch Axis Handling Qualities Parameter
cg	Center of Gravity
D^*	Roll-Yaw Coordination Handling Qualities Parameter
D_1^*/k	Normalized D^* Response
$\dot{D}_1^*/k$	Normalized $\dot{D}^*$ Response
ft	Foot
g	Acceleration due to Gravity
h	Altitude
$\dot{h}$	Altitude Rate
i	Current
IP	Information Processing Workload
k	Ratio of "commanded roll performance" to "applicable roll performance requirement"
$\bar{L}$	Left Hand Workload
m	Mass
M	Mach Number
Nz	Load Factor
p	Roll Rate
P_F	Probability of Failure
P_N	Normalized Roll Rate
$\dot{P}_N$	Normalized Roll Acceleration
P_s	Specific Excess Power
Q	Probability of Loss of Control Function
$\bar{q}$	Dynamic Pressure
r	Range
r	Pearson Product - Moment
$\dot{r}$	Range Rate

$\bar{R}$	Right Hand Workload
s	Second
t	time
v	volts
V	Velocity
$\bar{V}$	Visual Workload
$\bar{W}$	Workload
W_T	Total Pilot Workload
X_A	Actuator Coverage
X_C	Computer and I/O Coverage
X_S	Composite Sensor Coverage
X_2	Total Second Fault Coverage
α	Angle-of-Attack
β	Sideslip Angle
γ	Confidence Factor
γE	Gunsight Lead Angle
δ	Maximum Expected Difference in Computer Cycle Time
δ_c	Canard Deflection
ΔP	Incremental Roll Rate
ΔP	Differential Pressure
ΔR	Incremental Yaw Rate
ΔT	Nominal Computer Cycle Time
θ	Pitch Angle
λ	Channel Failure Rate
λ_A	Actuator Failure Rate
λ_{acc}	Accelerometer Failure Rate
λ_{act}	Actuator Failure Rate
$\lambda_{A/D}$	a/D Converter Failure Rate

λ_C	Computer and I/O Failure Rate
λ_{com}	Computer Failure Rate
$\lambda_{D/A}$	D/A Converter Failure Rate
λ_{PIT}	Pilot Input Transducer Coverage
λ_{RG}	Rate Gyro Failure Rate
λ_S	Composite Sensor Failure Rate
μ	Maintenance Action Rates
μ_{OH}	Maintenance Actions per Million Operate Hours
ρ	Density
ϕ	Bank Angle
$\sim$	Approximately Equals

1.0 INTRODUCTION AND SUMMARY

This report presents the results of a Definition Study for an Advanced Fighter Digital Flight Control System. A synergistic combination of flight control capabilities and extensive crew system integration was defined through a series of studies and simulations and evaluated by service pilots in a comprehensive simulation program. Significant improvements in tactical effectiveness with reduced pilot workload were found.

Customized flight control modes were designed for specific mission segments to provide enhanced tactical effectiveness. The capabilities for relaxed static stability and both direct lift and direct side force control were incorporated into these customized control modes. In addition, provisions were included which enable flight at high angles-of-attack without the danger of aircraft departure or overstressing.

Crew system integration was accomplished to give capabilities never before present in a fighter aircraft while at the same time reducing pilot workload and required instrument panel area. Head-up and multi-function displays were provided for presentation of data keyed to the flight control mode selected and needed by the pilot to accomplish his immediate objective. Hands-on-stick-and-throttle weapon and mode control were provided for all tasks requiring rapid access. A flight management capability was implemented to provide for position fixing, flight plan management, airport approach and departure procedures, and electronic warfare data required to support tactical fighter operations. The flight management implementation also provides a fully automatic three dimensional area navigation system capable of navigating directly between any two points as well as on airways, SIDs, STARs, and RNAV routes. A computer and display controller was included which demonstrated a simple and effective means of communication between the pilot and computers. The flight management computer, rather than the pilot, performs navigation sensor management, such as frequency selection and initialization. These flight management characteristics have provided a significant step toward enabling the pilot to become a mission-oriented manager rather than a subsystem operator.

Fly-by-wire (FBW) controls have been the catalyst that make the above advancements possible, and digital technology provides the flexibility and computational capacity to implement these capabilities in a cost-effective manner.

The Definition Study for an Advanced Fighter Digital Flight Control System is a joint Air Force and Navy exploratory definition study performed by McDonnell Aircraft Company (MCAIR) as prime contractor to the Air Force Flight Dynamics Laboratory (AFFDL) to consolidate the large amount of general foreground research in digital flight-control and display technology. General Electric, Honeywell, Lear Siegler and Collins supported MCAIR in the analyses and simulations associated with this program. This study is a precursor to an Advanced Development Program (ADP) to accomplish flight validation of the design criteria and the performance and cost advantages promised by these technologies when applied to advanced tactical fighter aircraft.

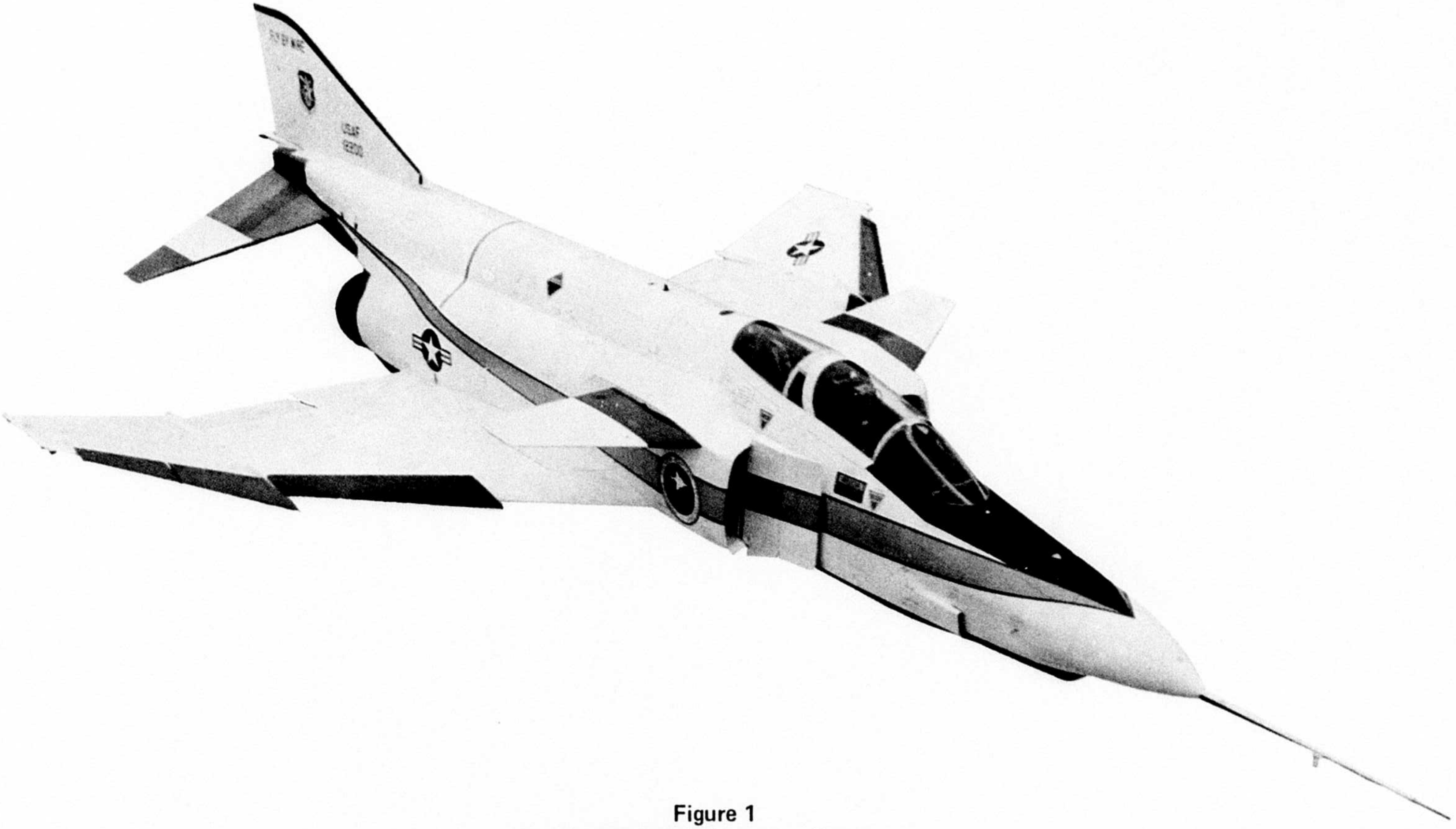


Figure 1
F-4 S/N 62-12200 ''Test Case'' Aircraft

The objectives of the Digital Flight Control System (DFCS) Definition Study are:

- o Derive and Evaluate for Advanced Air Force and Navy Tactical Fighters:
  - o Custom Multimode Control Laws (matched to segments of a tactical mission)
  - o Displays Pertinent to Each of the Multimodes
  - o Multi-Channel Digital FBW Configurations
- o Develop New Performance - Cost - Time Options
- o Define Candidate Flight Control and Display Schemes
- o Define a Recommended ADP Configuration

The Precision Aircraft Control Technology (PACT) configuration of F-4 S/N 62-12200, modified to include differentially controllable canards, was used as the "test case" aircraft, Figure 1, for analytical and simulation efforts during this study. The conceptual design of the Digital FCS is for a single-place fighter having the capability of performing Air Force and Navy mission tasks defined by a 14-segment Mission Scenario, Figure 2. The scope of the cockpit controller and display study and other integration effort was limited to include only those functions which are flight control related. Other controllers and display functions such as those relating to Communications, Armament, and Engine Instruments were excluded. The overall approach utilized by MCAIR in performing this study is depicted by Figure 3.

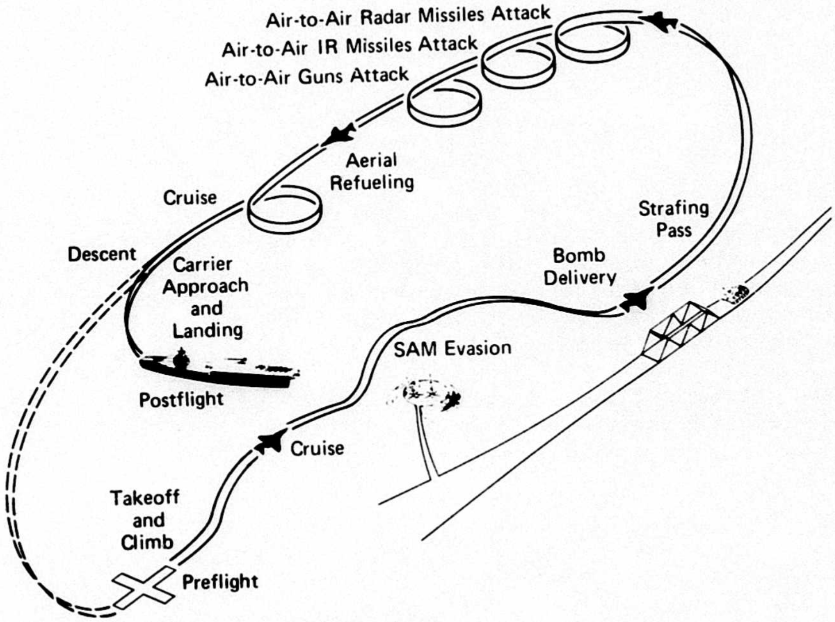


Figure 2
Air Force and Navy Tactical Fighter
Composite Mission Profile

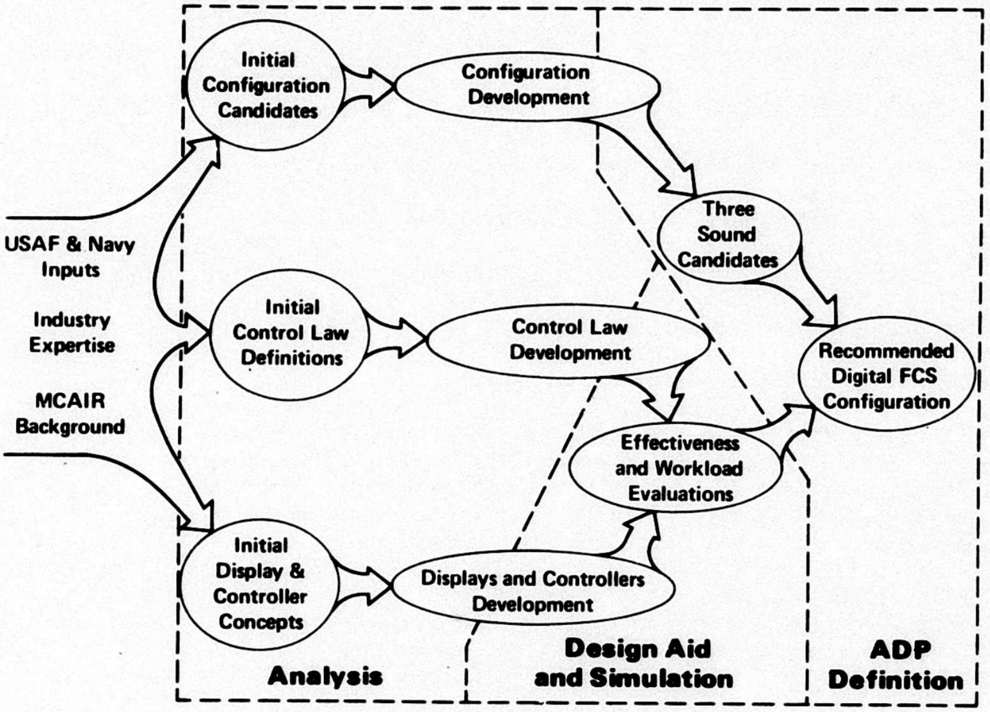


Figure 3
Approach

A summary of the analytical studies performed and the results of analyses and simulations are presented in Section 2.0. A description of the testing and evaluations performed on the design aid, advanced fighter mockup and man-in-loop simulations is contained in Section 3.0. A recommended configuration for an Advanced Development Program is presented in Section 4.0. Support provided by four companies under subcontract to MCAIR is described in Section 5.0.

Manual and automatic flight control modes developed, evaluated in simulation, and recommended for ADP are presented in Figures 4 and 5.

Evaluated During Man-in-the-Loop Simulations	Recommended for Incorporation Into ADP
• Normal	• Normal(1)
• Gear Up: Cruise	• Gear Up: Cruise
• Gear Down: Airfield Takeoff and Landing	• Gear Down: Airfield and Carrier Takeoff and Landing
• Carrier Takeoff and Landing	
• Air-to-Air Combat	• Air-to-Air Combat
• With Planar Turn	
• Without Planar Turn	• Without Planar Turn
• Air-to-Ground Bombing	• Air-to-Ground Bombing
• Air-to-Ground Gunnery	• Air-to-Ground Gunnery
• Fixed Canards	
• DigiPACT(2)	• DigiPACT(2)

(1) Includes Operable and Fixed Canards

(2) DigiPACT - Digital Implementation of SFCS-PACT Control Laws (Provided for Purposes of Comparison)

Figure 4
Manual Modes for the ADP

Evaluated During Man-In-The-Loop Simulations	Recommend For Incorporation Into ADP
• Pitch Attitude Hold	• Pitch Attitude Hold
• Roll Attitude or Heading Hold	• Roll Attitude or Heading Hold
• Altitude Hold	• Altitude Hold
• Preselect Heading	• Preselect Heading
• Automatic Throttle	
• Automatic Vertical Navigation	• Automatic Vertical Navigation
• Automatic Lateral Navigation	• Automatic Lateral Navigation
• Automatic Carrier Landing	

Not Evaluated During Man-In-The-Loop Simulations	Available Options For ADP
• Automatic ILS	• Automatic ILS
• Automatic Energy Management	• Automatic Energy Management
	• Automatic Throttle
	• Automatic Carrier Landing

Figure 5
Automatic Modes for the ADP

A DFCS cockpit arrangement, Figure 6, evolved from an iterative process of evaluations and refinements of design layouts, mockups, and a full scale design aid. Features of this arrangement include:

- Principal mission and flight information presented on a Head-Up Display (HUD) and two CRT Multi-Function Displays (MFD I and II),
- Primary flight controllers mounted on the armrests of the seat,
- Redundant Computer and Display Controllers (CDC) for pilot-computer communications and central control of flight control modes and related displays, and
- Compatibility with high-acceleration cockpit concept.

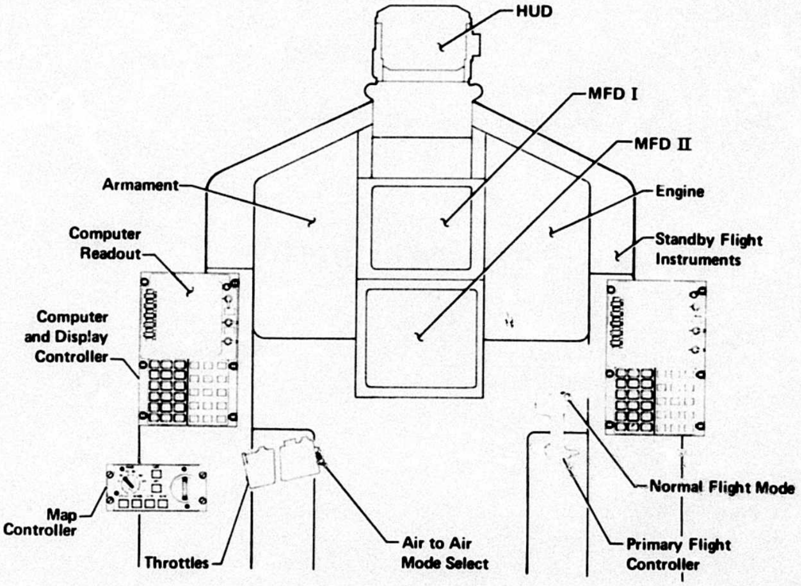


Figure 6
Cockpit Arrangement of Mode Related Displays and Controllers

Display information requirements and task identifications were determined from an analysis of the functions required to perform each of the segments of the mission scenario. Pilot workload was a factor of major consideration in the partitioning of display information and assignment of tasks for flight management. A comparison was made of pilot workloads calculated from data obtained during static and dynamic evaluations, for the DFCS and an Advanced Fighter currently in Air Force inventory. Figure 7, shows that the DFCS configuration resulted in a reduced workload for each of the seven segments simulated.

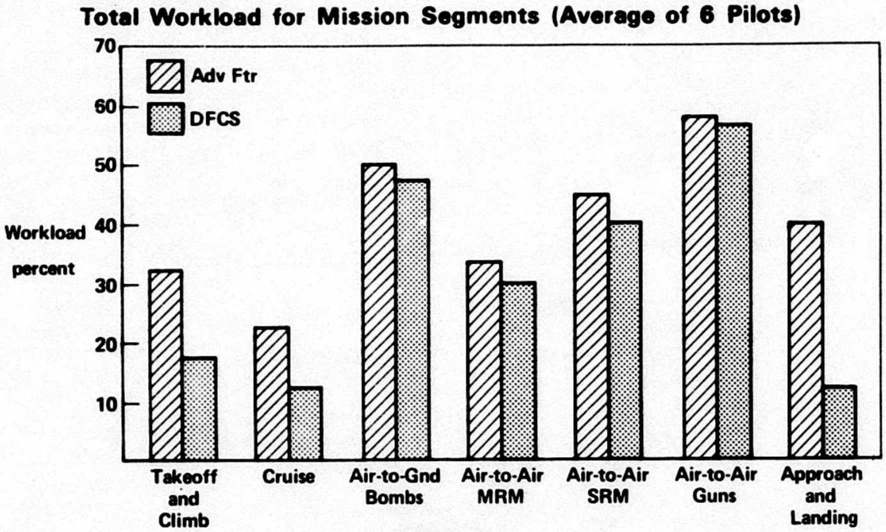
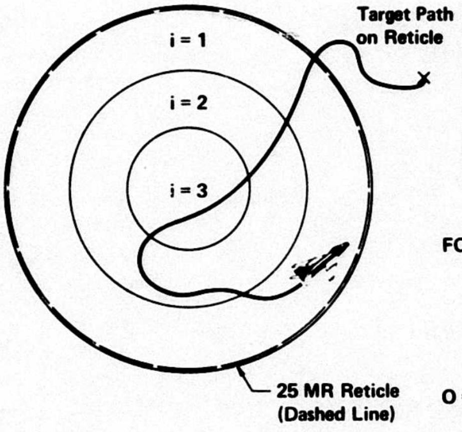


Figure 7
Workload Results
DFCS vs Advanced Fighter

A general-purpose fighter control law (DigiPACT) was used for purposes of comparison during man-in-loop simulations to determine the relative effectiveness of the customized DFCS control laws. Results obtained show that the pilots ability to perform specified mission tasks was enhanced when using the customized DFCS control laws. A sample of these tracking results is illustrated in Figure 8 for the customized air combat mode (ACM) and the general purpose DigiPACT mode.



Tracking Figure of Merit (FOM) Results

ACM Mode: 0.43

DigiPACT Mode: 0.31

$$\mathrm{FOM} = \frac{1}{3T} \sum_{i=1}^{3} i \cdot T_i$$

T_i = Target Time within Ring i

T = Total Tracking Time = 8 sec

$0 \leq \mathrm{FOM} \leq 1$

Figure 8
Integrated Control Law and Display Simulation
Representative Air-to-Air Combat Effectiveness Data

A triplex flight control system is recommended for evaluation in an ADP on the basis of studies conducted on six initial configuration candidates, Figure 9. A more detailed description of each configuration candidate is contained in Section 2.12. Comparative results of studies for the three "sound candidates" are shown in Table 1. These comparisons show that the triplex configuration features:

- Lowest weight
- Best maintainability
- Good reliability
- Lowest cost

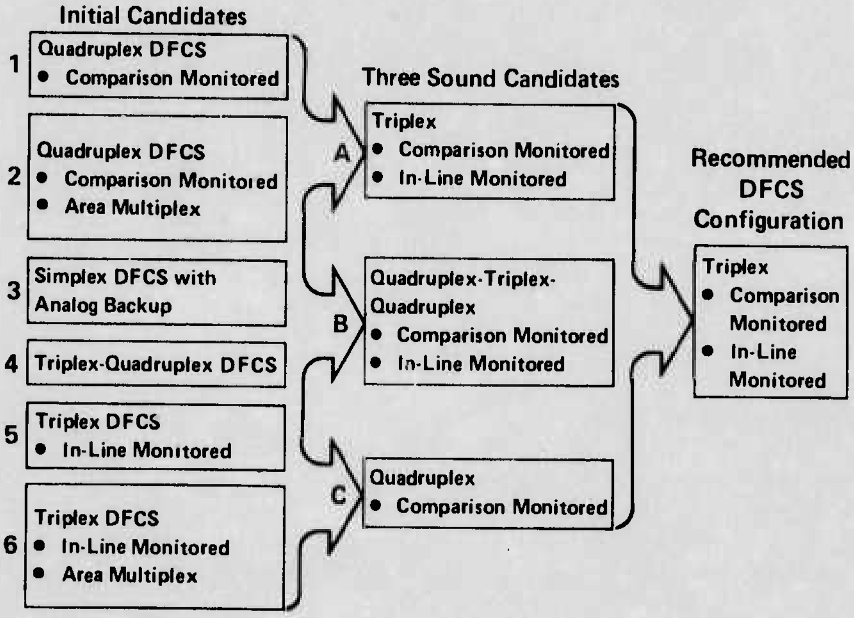


Figure 9
Configuration Development

Table 1
Three Sound Candidates
Summary of Analyses

Configuration	Performance, Safety and Survivability	Reliability (Probability of Loss of Control)	Maintainability (MMH/FH)	Relative Weight	Relative Cost
A (3-3-3)	Same	3.5×10^{-8}	0.262	1.00	1.00
B (4-3-4)	Same	2.3×10^{-9}	0.298	1.18	1.35
C (4-4-4)	Same	3.9×10^{-10}	0.309	1.18	1.42

A redundancy management scheme was defined to provide protection from loss of control through use of comparison monitoring to detect first failures and in-line monitoring to detect subsequent failures. Necessary computer capacity and capabilities to accomplish both the flight control mode and redundancy management implementation were assessed.

Studies and simulations indicate that mission-oriented flight control laws integrated with head-up and multi-function displays, hands-on-stick-and-throttle weapon and mode control, and computer and display controller for pilot-to-computer communications can provide:

- o Enhanced mission effectiveness, with
- o Reduced pilot workload.

The demonstrated capabilities of the computer and display controller to provide a simple and effective means of communication between the pilot and computers suggests the feasibility for integrating and time-sharing other pilot control functions. Potential benefits include: more efficient use of panel space, increased pilot efficiency, further reduction in pilot workload, and reduced cost of ownership.

It is recommended that the concepts analyzed and simulated during the definition study be implemented and evaluated by flight testing.

2.0 ANALYSES

2.1 GENERAL

This section presents a summary of the results of analyses conducted during the Digital FCS Study program by engineers with expertise in many technical disciplines. All analyses were designed to produce conclusions generally applicable to any advanced fighter aircraft. The fly-by-wire aircraft described in Section 1.0 was utilized as a "test case" for application of the results of these analyses.

This section discusses analyses in the following subsections:

- Mission-Scenario Analysis
- Evaluation Criteria
- Control Law Development
- Electrical Backup (EBU)
- Pilot Interface
- Displays and Controllers Development
- Multiplex Analysis
- Lightning Protection
- Electromagnetic Compatibility (EMC)
- Built-In Test and Inflight Integrity Management (BIT and IFIM)
- Redundancy Management and/or IFIM Analysis
- Analysis of Industry Expertise
- Software Analysis
- Single-Point-Failure Analysis
- Safety Analysis
- Reliability Analysis
- Maintainability Analysis
- Effectiveness Analysis
- Workload Analysis
- Survivability Analysis
- Cost-of-Ownership Analysis

2.2 MISSION-SCENARIO ANALYSIS

2.2.1 GENERAL - A mission scenario was provided to the Contractor by the Program Office. Simulated takeoffs were performed from an AF facility and simulated landings were accomplished at both an AF facility and on an aircraft carrier. The composite mission profile is illustrated in Figure 2.

Mission Segments are:

(1) Preflight
(2) Takeoff and Climb, AF Facility
(3) Outbound Cruise
(4) Penetration and SAM Evasion
(5) Bomb Delivery
(6) Strafing Pass
(7) Air-to-Air Radar Missiles Attack
(8) Air-to-Air IR Missiles Attack
(9) Air-to-Air Guns Attack
(10) Aerial Refueling
(11) Inbound Cruise
(12) Enroute Descent with Holding
(13) Approach and Landing
    (a) AF Facility, or
    (b) Carrier Environment
(14) Postflight

2.2.2 METHODS - The mission scenario was divided into specific mission segments as outlined in Section 2.2.1. Each segment was analyzed on a time base to determine the functions required. An evaluation of each function was then performed to establish the information requirements. Individual mission tasks also were identified by further subdividing the functions associated with each mission segment. An analysis of the mission tasks and the information requirements produced the data necessary to determine opportunities for time-shared versus dedicated displays and controllers. This analysis also provided the basis for deciding which functions should be automated and which should be done manually. The sequence of analyses is shown in Figure 10.

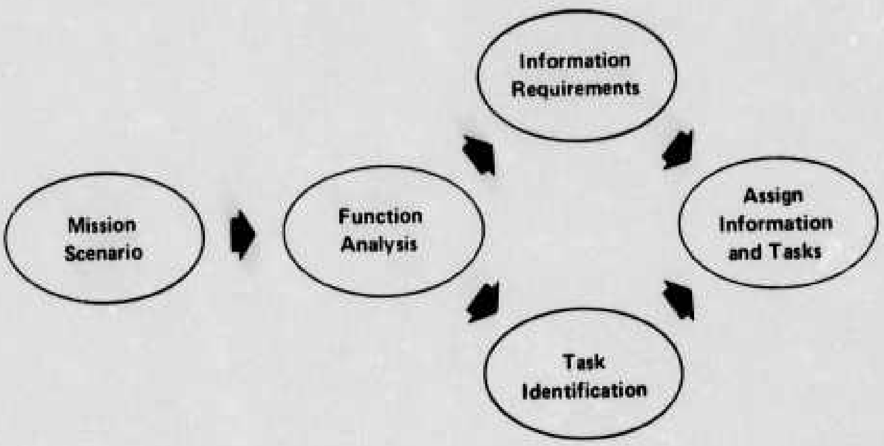


Figure 10
Mission Scenario Analysis

2.3 EVALUATION CRITERIA

2.3.1 GENERAL - A set of properly structured criteria was necessary for evaluating the change in effectiveness and pilot workload resulting from the incorporation of multimode control laws and advanced displays. It was desirable that the criteria selected for these evaluations be applicable both for use in the analysis, mockup and simulations performed during the Digital FCS Definition Study and for subsequent flight testing to be performed under the ADP. The criteria selected during this DFCS Definition Study for effectiveness evaluations are expressed in terms of tracking errors. The criterion for pilot workload evaluations is expressed in terms of the ratio of time required to perform a task sequence to the time available for its performance. A discussion of these criteria is presented below.

2.3.2 EFFECTIVENESS CRITERIA - The effectiveness evaluation criteria used throughout the analysis and simulation phases of the DFCS Definition Study were based on tracking error and tracking error statistics obtained during gun-cross ("iron sight") tracking. The tracking error statistics consisted of the means and variances of the tracking error elevation and traverse components. These criteria enable an evaluation of the capability of the Digital FCS configured fighter aircraft to deliver its ordnance accurately.

The above effectiveness criteria were chosen in order to maintain consistency in evaluating the Digital FCS during the analysis and simulation phases of this study and for their applicability to future flight test data reduction. Although the fire-control system to be used during flight testing under the ADP may not consist of a simple gun-cross mechanization, the use of tracking error statistics with a simple "iron sight" can always be used as a basic measure of effectiveness regardless of the type of fire-control system or weapons that are being considered for the weapon system. Tracking errors will reflect differences in flight control system characteristics regardless of fire-control and weapon characteristics.

Examples of the application of these effectiveness criteria to analytical and man-in-the-loop simulation data for the multimode control laws are presented in Section 2.19 of this report.

2.3.3 PILOT WORKLOAD CRITERIA - The pilot workload evaluation criterion used during analysis, mockup, and simulation phases of the Digital FCS Definition Study was expressed in terms of the ratio of time required to perform the tasks required during each segment to the time available for their performance. Workload was calculated separately for visual, right hand, left hand, and information processing. Figure 11 summarizes the pilot workload criteria. This type of workload criteria was used in conducting the workload analyses in the High Acceleration Cockpit (HAC) contracts cited in References (1) and (2).

References:

1. High Acceleration Cockpits for Advanced Fighter Aircraft. Contract No. F33615-73-C-3067. AFFDL, Wright-Patterson AFB, Ohio.
2. High Acceleration Cockpit Variable Seat/Control Assembly. Contract No. F33615-73-C-0565. AeroMed Research Laboratory.

- **Workload is Expressed as a Percentage:**

$$\overline{W} = \frac{\text{Time Required to Perform Tasks} \times 100}{\text{Time Available}}$$

- **Workload is Calculated Separately for Visual ($\overline{V}$), Right Hand ($\overline{R}$), Left Hand ($\overline{L}$) and Information Processing ($\overline{IP}$), For Example:**

$$\overline{R} = \frac{\text{Time Required to Perform Right Hand Tasks} \times 100}{\text{Total Mission Segment Time}}$$

- **Total Pilot Workload:**

$$W_T = \overline{V} + \overline{R} + \overline{L} + \overline{IP}$$

Figure 11
Pilot Workload Criteria

To achieve the effective integration of man into the developed configuration, the principles and criteria of human engineering contained in MIL-STD-1472A, AFSC DH1-3, MIL-C-81774, MIL-H-46855, and other applicable design criteria, standards, and specifications were applied throughout the Digital FCS study. The introduction of a flight management system achieved significant improvements in workload by establishing a simple and effective means of communication between the flight management computer and the pilot, by eliminating routine tasks traditionally performed by pilots, and by restructuring the information available for the decision process. Automation of the flight activities and integration of the flight control modes with relevant display formats also reduced task complexity and pilot workload. These flight management system characteristics have provided a significant step toward enabling the pilot to become a mission oriented manager rather than a subsystem operator.

The results of the application of this pilot workload evaluation criteria to the Digital FCS are presented in Section 2.20.

2.4 CONTROL LAW DEVELOPMENT

2.4.1 INTRODUCTION - A set of control laws was developed for the "test case" aircraft employing the use of ailerons, spoilers, stabilator, rudder, split horizontal canards, cockpit control devices, and engine thrust. The canards were collectively operable for pitch and Direct Lift Control (DLC), and differentially operable for Direct Side Force (DSF) control.

The control laws utilized the advantages of both full-authority digital fly-by-wire techniques and pilot-essential displays to enhance flight safety, combat survivability, and mission accomplishment. In its modified configuration, the "test case" aircraft represents an advanced fighter with a mission profile suitable for both the Navy and Air Force roles. Therefore, the control law design emphasized air superiority, interdiction, close-air-support, and fleet-air-defense. The control laws were divided into two major groups; namely, manual (pilot-assist) modes and automatic (pilot-relief) modes. Those pilot-assist modes developed for weapon delivery were designed for increased effectiveness; the other modes were designed for improved handling qualities.

The design approach to developing the control laws was first to establish good continuous control systems based on classical continuous synthesis and analysis techniques and subsequently to consider the digitization of the control laws. The design task was accomplished using small perturbation airframe models in conjunction with root locus, frequency response, and time history computer programs which were adapted for this purpose. Section 2.4.2 presents the handling qualities criteria used in the development of the control laws. Sections 2.4.3 through 2.4.7. then describe the initial control law design in the continuous form. Following this initial design, the control laws were evaluated and refined during man-in-the-loop simulations as discussed in Sections 3.3.1 and 3.3.3.

2.4.2 HANDLING QUALITIES CRITERIA

- MIL-F-8785B
- Specialized Mode Criteria
- Time Response Criteria
  - C* Criterion
  - D* Criterion
  - Roll Axis Response Criterion
  - Time Response Parameter (TRP)

As a guide in the development of the DFCS Control Laws, a number of handling qualities criteria were identified in a literature search and reviewed for applicability to the control modes. These criteria fall into three basic categories:

- Handling qualities criteria typified by the MIL-F-8785B Reference (3) handling qualities specification and Reference (4),

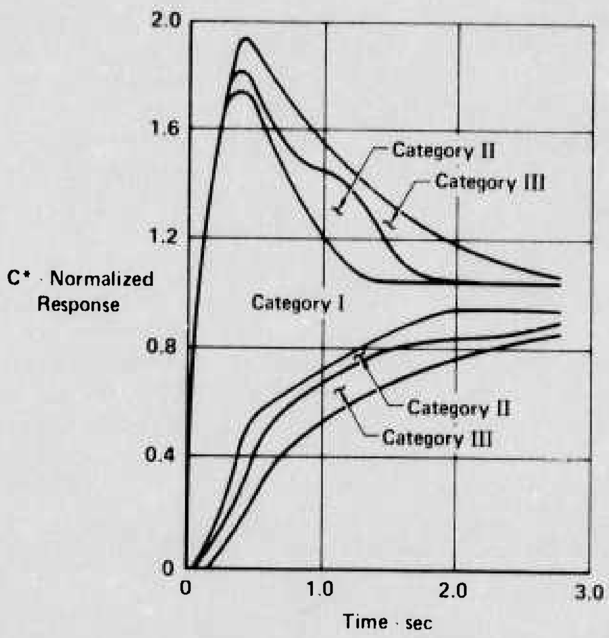
References:

3. "Flying Qualities of Piloted Airplanes," MIL-F-8785B (ASG), 7 August 1969.
4. Abrams, C. R.; "The Effects of Rudder Feedback on the Carrier Approach Configuration of the F-111B", Report No. NADC-AM-6816, Naval Air Development Center, Warminster, Pa., 1968.

- Time response criteria including response envelopes as in References (5) and (6), and the Time Response Parameter (TRP) Index from Reference (7), and

- System requirements for specialized modes such as the Automatic Carrier Landing criteria in Reference (8), and the ILS criteria as defined in Reference (9).

Figures 12 through 14 present the time response criteria envelopes from References (5), (6) and (7).



Category	Applicable Tasks
I	Ground Attack Penetration and Aerial Combat
II	Refueling and Cruise
III	Loiter

Figure 12
C* Response Criterion

References:

5. Tobie, H. N., Elliott, E. M., "New Short Period Handling Quality Criterion for Fighter Aircraft", Boeing Document No. D6-17841 T/N, September 1965.

6. Kisslinger, R. L. and Wendl, M. J.; "Survivable Flight Control System Interim Report No. 1 Studies, Analysis and Approach", Supplement for Control Criteria Studies, AFFDL-TR-71-20 Supplement 1, May 1961.

7. Abrams, C. R.; "A Performance Index for Response Evaluation of Highly Augmented Military Aircraft", Report No. NADC-AM-7103, Naval Air Development Center, Warminster, Pa., 12 October 1971.

8. "All-Weather Carrier Landing System Airborne Subsystem, General Requirements for", Report No. AR-40, Naval Air Systems Command, 1 May 1969.

9. FAA Advisory Circular AC 120-29, "Criteria for Approving Category I and Category II Landing Minima for FAR 121 Operators", 25 September 1970.

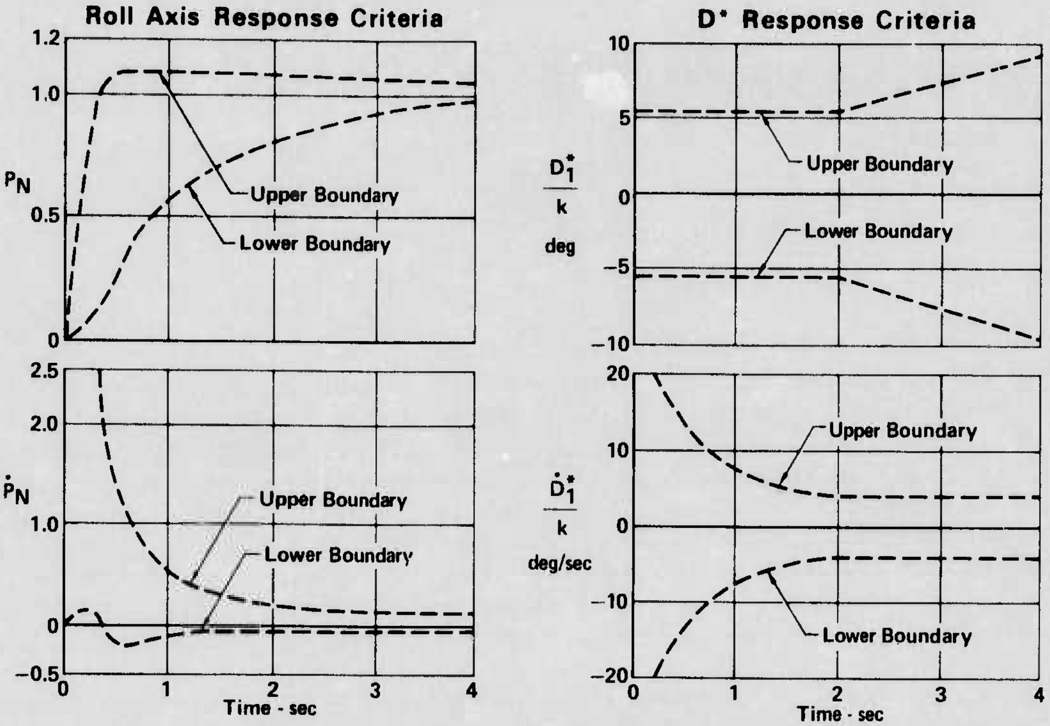
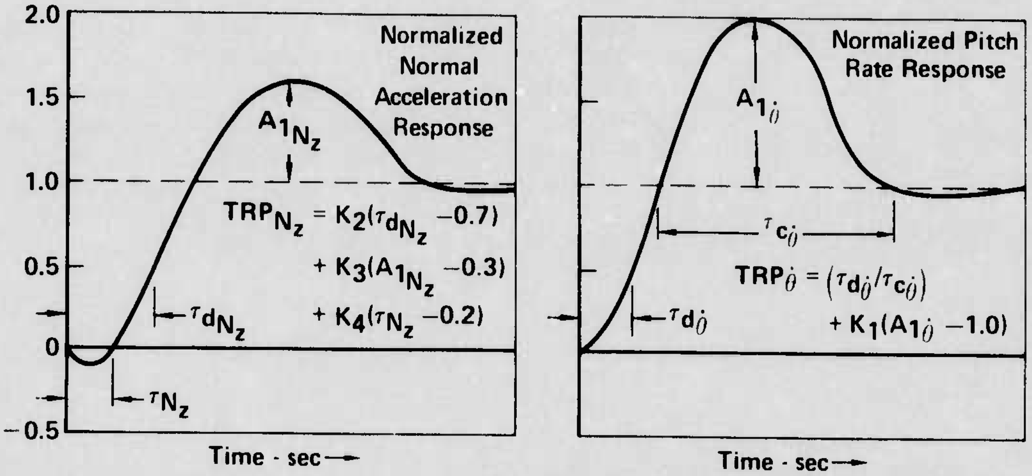


Figure 13
Roll Axis and D* Response Criteria



Nominal Values
$K_1 = 0.08$
$K_2 = 0.5$
$K_3 = 0.3$
$K_4 = 0.2$

Correlation Between Cooper-Harper Pilot Rating (PR) and TRP (Abrams)

PR	TRP
$1 \leq PR \leq 3.5$	$0.16 < TRP < 0.23$
$4 \leq PR \leq 6.5$	$0.27 < TRP < 0.43$
$7 \leq PR \leq 10$	$0.34 < TRP < 0.98$

Figure 14
Time Response Parameter (TRP)
$TRP = TRP_{\dot{\theta}} + TRP_{N_z}$

2.4.3 MANUAL (PILOT-ASSIST) MODES

- o Normal
- o Air-to-Air Combat
- o Air-to-Ground Bombing
- o Air-to-Ground Gunnery
- o Manual Carrier Landing
- o Fixed Canards
- o DigiPACT

Pilot-assist modes were developed to assess the feasibility and desirability of incorporating into the Digital FCS certain customized multimodes which integrate vehicle control with mission demands to improve weapon-system effectiveness as defined in Section 2.3.2. The multimodes provide for enhanced mission effectiveness in tactical missions such as strafing, bombing, missile launch, target tracking, aerial refueling, and landing. The modes developed for these missions are the Normal Mode, Air-to-Air Combat Mode, Air-to-Ground Bombing Mode, Air-to-Ground Gunnery Mode and Manual Carrier Landing Mode. The TWeaD control laws reported in Reference (10) were used as a source of control law methodology for these modes. The results of the multimode studies reported in Reference (11) were also utilized.

Two additional pilot-assist modes, the DigiPACT Mode and Fixed Canards Mode, were included in the study. The DigiPACT Mode is a general-purpose mode (in contrast to the previously mentioned customized multimodes) and was employed as a comparison mode; the Fixed Canards Mode was developed to provide adequate handling qualities (Category 2 of Reference (6)) in the pitch axis in the event of a failure in the canard control path.

Control laws incorporating active feedback elements which enable direct pilot control of aircraft motion were developed for all pilot-assist modes. Pitch rate, roll rate, yaw rate, normal acceleration and lateral acceleration feedbacks were utilized to provide control of aircraft rates and accelerations as well as to damp aircraft response to external environmental disturbances. Sideslip and angle-of-attack (AOA) signals were also included in the design of some of the modes.

2.4.3.1 Normal Mode

Features

- o Uniform transient response
- o Neutral Speed Stability - Gear Up
- o Improved turn coordination
- o Direct Lift capability
- o Lateral Translation capability

References: 10. Carleton, D. L., et al, "Development and Evaluation of the TWeaD II Flight Control Augmentation System", Technical Document FTC-TD-72-1, Edwards AFB, California, August 1971.

11. Quinlivan, R. P., "Multimode Flight Control Definition Study for Precision Weapon Delivery", Technical Report AFFDL-TR-71-39, Wright Patterson AFB, Ohio, June 1971.

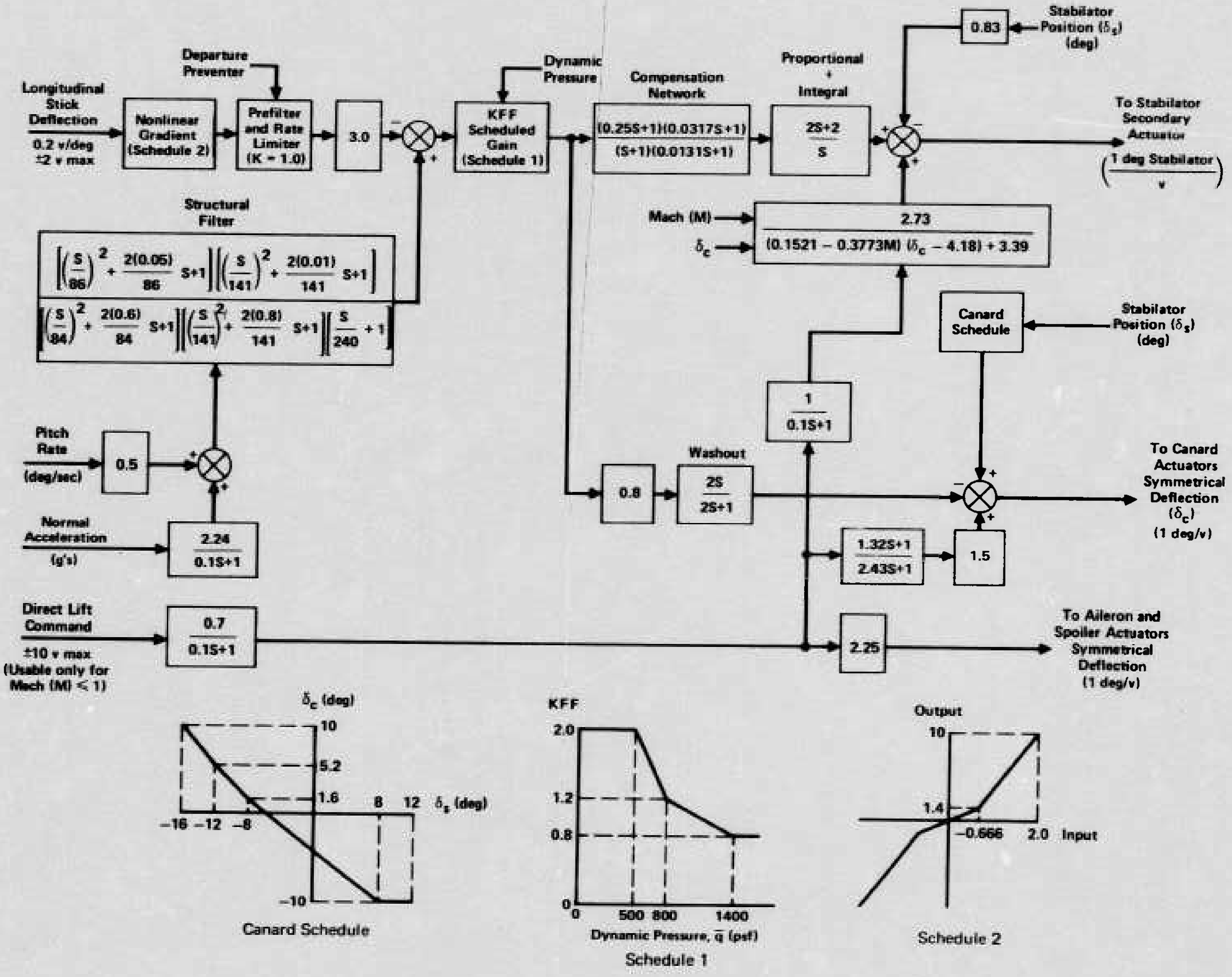
- o Reduced accelerations due to gusts
- o Departure prevention

The Normal Mode was designed for use throughout the applicable flight envelope for takeoff, cruise, and landing, either clean or with stores. In addition, it was used for all mission segments including weapon delivery in the absence of specialized modes. The design of the Normal Mode included selection of the most effective feedback variables and use of handling qualities criteria described in Section 2.4.2 to achieve reduced control system and airframe sensitivity to variations in flight conditions. The primary purposes of the Normal Mode were to:

- o Function as the principal control law used in up-and-away flight,
- o To provide a good starting point for the development of the other pilot-assist modes, and
- o To provide the basic inner loop stabilization for the specialized pilot-relief modes.

(a) Longitudinal Axis - A block diagram of the Normal Mode longitudinal axis control law is presented in Figure 15. The longitudinal control surfaces are the stabilator and close-coupled horizontal canards geared together through a canard schedule to provide minimum maneuvering drag. A "speed-up" control signal was provided through a washout network to the canard in addition to the canard schedule signal. The purpose of the "speedup" signal was to provide anticipation to achieve quicker responses to longitudinal input commands. Feedback signals consisted of a blend of pitch rate and normal acceleration. Neutral Speed Stability (NSS) was provided through the use of integral-plus-proportional control in the forward path to compensate for the change in trim requirements due to changes in aircraft speed and altitude. In order to achieve a satisfactory balance of stability margins and transient response performance over the flight envelope, the forward loop gain was scheduled with dynamic pressure as discussed in Section 2.4.5. A Departure Preventer was incorporated in the design as discussed in Paragraph (c).

A Direct Lift capability which permits small changes in altitude without changes in pitch attitude was provided in the longitudinal Normal Mode through a thumb-operated controller on the SSC. The Direct Lift feature employed the stabilator, symmetrically deflected canards, and symmetrically deflected ailerons and spoilers. Networks required to decouple the pitch and altitude responses were designed in an open loop fashion. This approach to implementing DLC required control network parameter scheduling since the decoupling networks varied with flight condition and control surface deflection. Scheduling could be minimized if tasks requiring DLC were performed at a limited number of flight conditions. The Normal Mode control laws had the DLC optimized for refueling (approximately 0.7 Mach at 20,000 ft) and landing.



$$\frac{\left[\left(\frac{S}{86}\right)^2+\frac{2(0.05)}{86}S+1\right]\left[\left(\frac{S}{141}\right)^2+\frac{2(0.01)}{141}S+1\right]}{\left[\left(\frac{S}{84}\right)^2+\frac{2(0.6)}{84}S+1\right]\left[\left(\frac{S}{141}\right)^2+\frac{2(0.8)}{141}S+1\right]\left[\frac{S}{240}+1\right]}$$

Figure 15
Normal Mode
Longitudinal Axis Block Diagram

The two-slope nonlinear gradient used to transform longitudinal pilot force inputs into an electronic signal is presented in Figure 16. Two different sidestick controllers were used in the manned simulation evaluations and each controller produced the same nonlinear output characteristics as illustrated in Figure 16. Breakout forces were approximately 1.6 lb. and the small slope near the null force reduced stick sensitivity for small inputs.

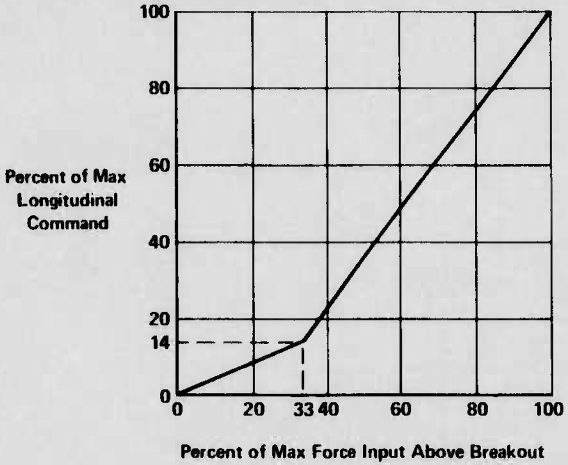


Figure 16
Longitudinal Stick Shaping

Figure 17 presents normalized C* responses for the Normal Mode clean configuration at three well separated flight conditions. Design goals were to meet the Category II C* boundaries presented in Figure 12. The TRP index, presented with each flight condition in Figure 17, was computed per Reference (7).

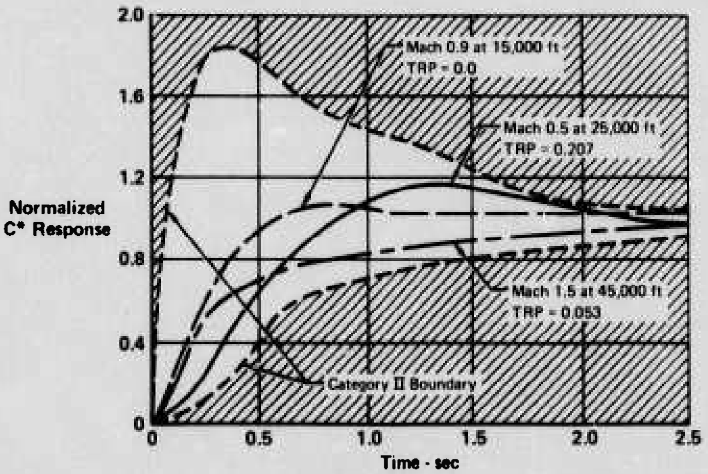


Figure 17
Normalized C* Responses with TRP Index
DFCS Normal Mode

(b) Lateral-Directional Axes - Figure 18 is a block diagram of the Normal Mode lateral-directional control laws. Lateral-directional control surfaces are the ailerons and spoilers in the lateral axis and the rudder and differential horizontal canards in the directional axis. Differential canards were reserved for Lateral Translation capabilities only. The lateral axis utilized proportional roll rate feedback. The directional axis employed washed out proportional yaw rate feedback for yaw damping and proportional-plus-integral feedback of blended sideslip angle and

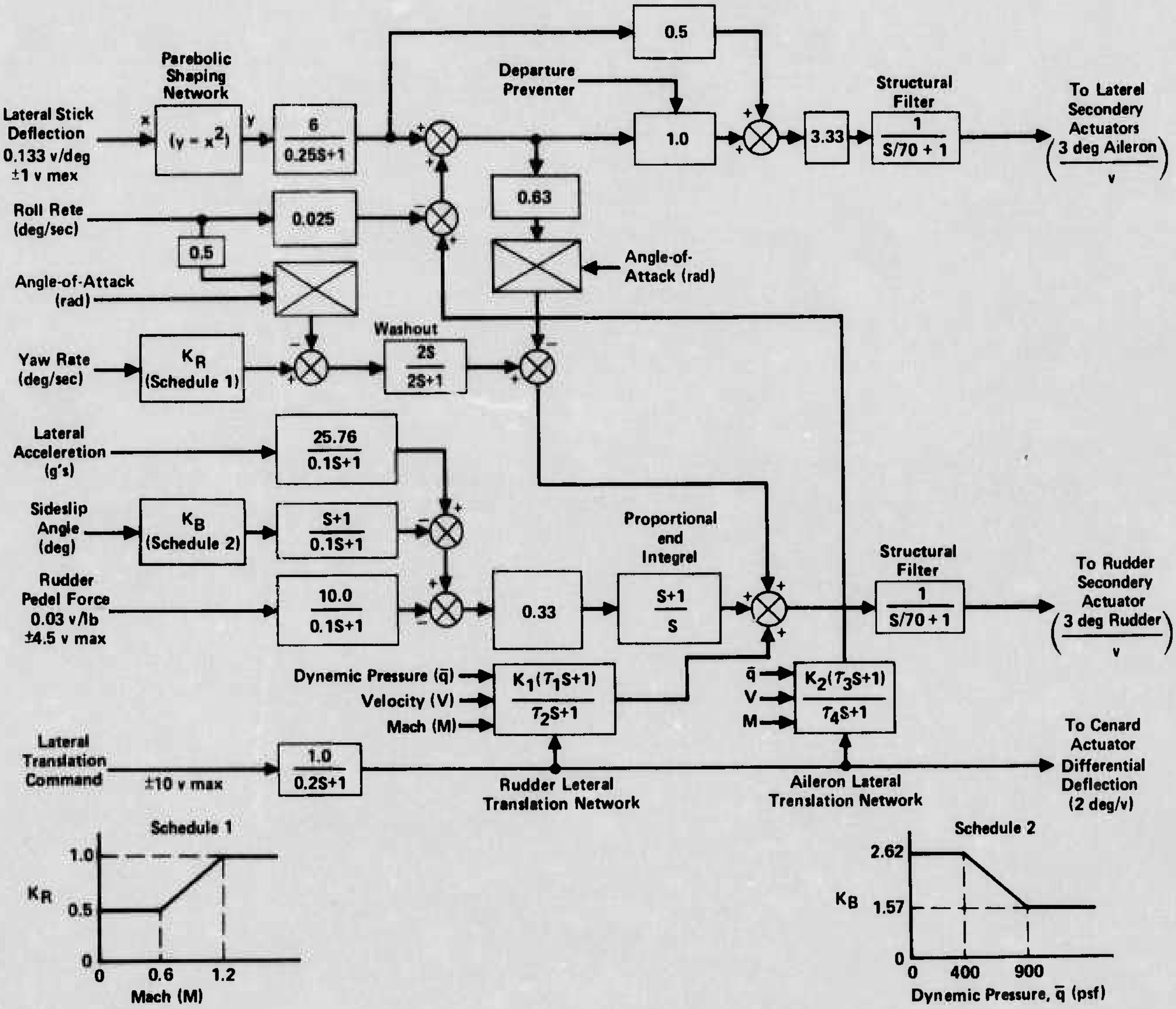


Figure 18
Normal Mode
Lateral-Directional Axes Block Diagram.

lateral acceleration. This arrangement provided good dutch-roll damping and turn coordination during roll maneuvers. Crossfeeds of roll rate multiplied by AOA ($P \cdot \alpha$), and of scheduled roll rate error signals as a function of AOA were provided to further improve turn coordination. Principal design criteria for these axes were the roll rate and D* handling qualities criteria (Figure 13) developed in the SFCS program. Representative Normal Mode lateral-directional roll rate and D* time responses are presented in Figures 19 and 20.

A Lateral Translation capability was available in the Normal Mode through a thumb operated controller on the SSC. Lateral Translation was used to command small sideslip angles without changing heading or roll attitude. The networks for Lateral Translation were defined in the same open loop manner as the DLC networks in the longitudinal axis, thus the lateral-translation-network parameters were also scheduled with flight condition.

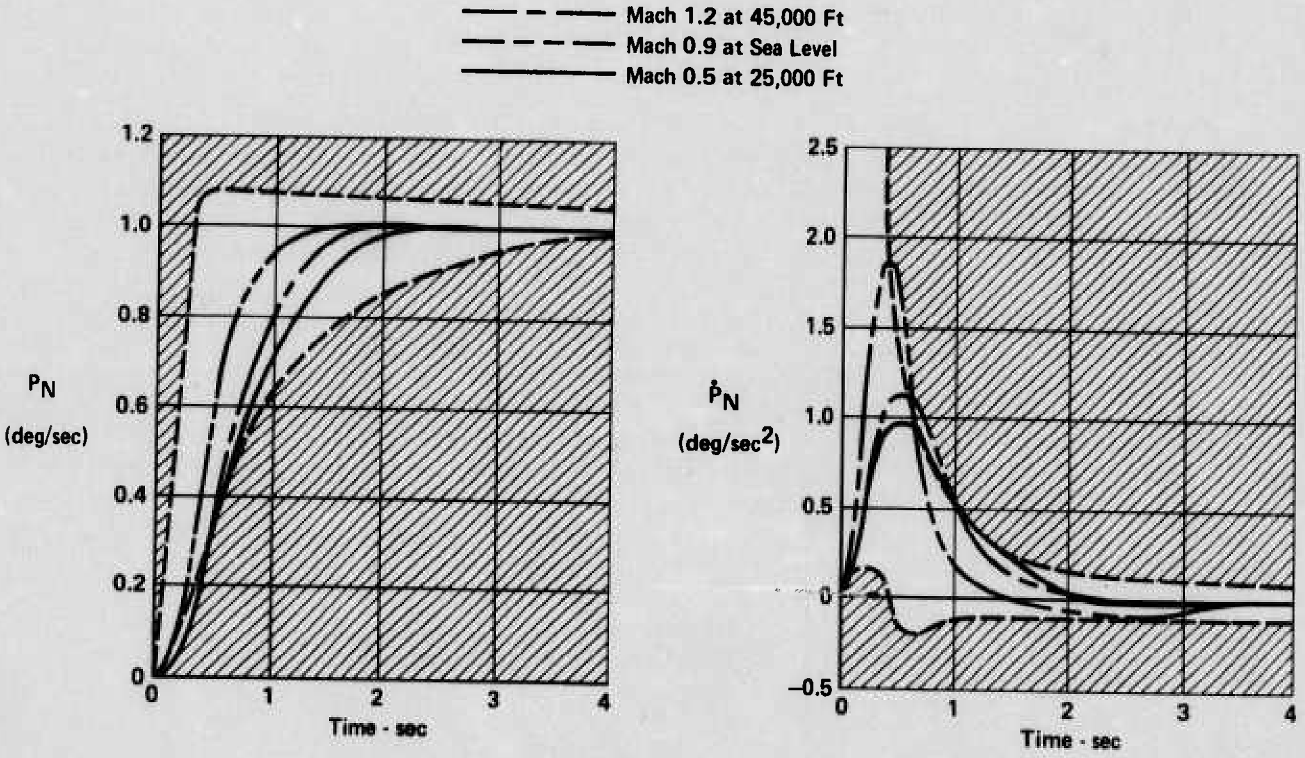


Figure 19
Normalized Roll Axis Response
DFCS Normal Mode

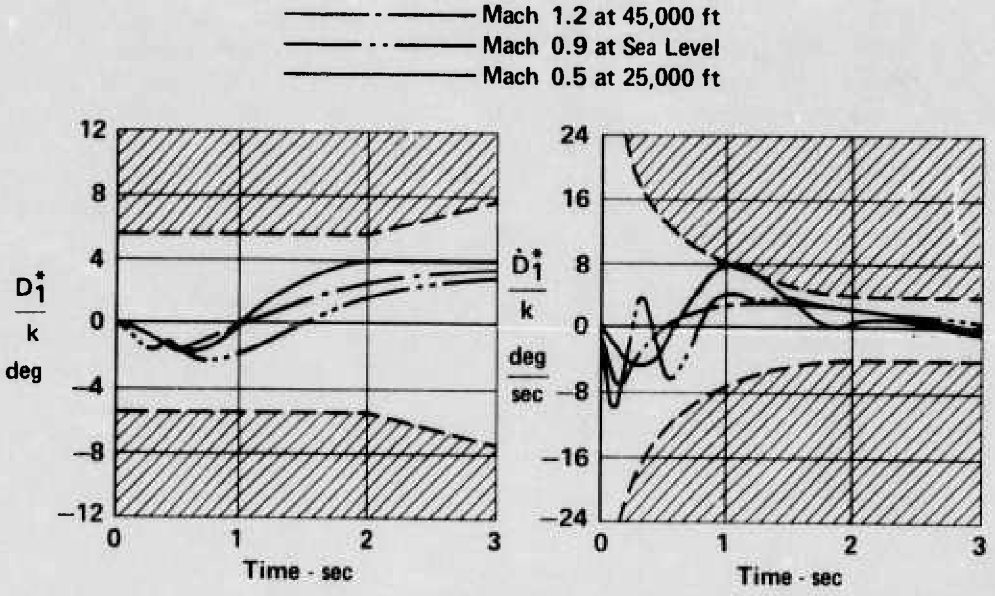


Figure 20
Normalized D* Response
DFCS Normal Mode

The parabolic shaping network used to convert lateral pilot force inputs into electronic command signals is presented in Figure 21. Included in Figure 21 is the three-slope gradient used for shaping in the SFCS and Precision Aircraft Control Technology (PACT) flight test programs, and retained for the DigiPACT mode.

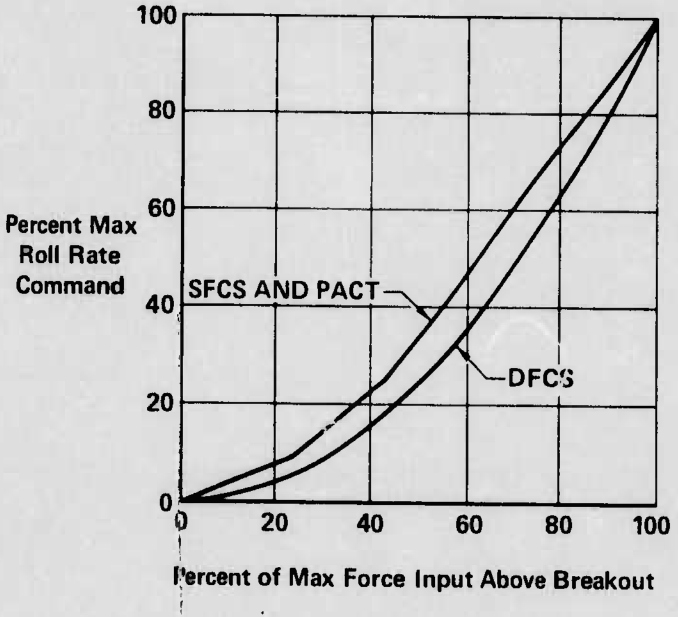


Figure 21
Roll Rate Command Shaping

(c) Departure Preventer - One of the primary features of all of the multimode control laws is that aircraft motion is the controlled variable rather than control surface position. A Departure Preventer was included to prevent the pilot from inadvertently commanding excessive g loads beyond the aircraft structural limits or from driving the aircraft into uncontrollable angles-of-attack. The Departure Preventer modified the longitudinal and lateral axes control laws as the aircraft load factor, AOA and sideslip angle approach control limits so that the limits were not exceeded and adequate control was maintained. In the longitudinal axis, the Departure Preventer functioned by controlling the rate limit of the prefilter. Measured values of AOA, sideslip angle and load factor were compared to schedules in the Departure Preventer, and the prefilter rate limits adjusted so that the most adverse pilot inputs would not cause the aircraft response to exceed the safe limits of the measured variables. Sufficient authority was given to the Departure Preventer to permit a change in sign of the pilot input, if necessary, to prevent exceeding those safe limits.

Statically unstable aircraft such as the "test case" aircraft place stringent requirements on longitudinal control surface rates. If rates are not high enough to permit rapid pilot inputs to be followed, the effective gain in the longitudinal control loop can be driven to a reduced value to the point that limit cycle oscillations will occur. For this reason, the maximum values of the Departure Preventer-adjusted prefilter rate limits were set to keep the stabilator from rate limiting for large, sharp pilot commands.

In the lateral axis, as AOA increased, the Departure Preventer reduced the roll rate feedback gain until the limit AOA was reached, at which time the roll rate feedback was reduced to zero and the pilot had direct proportional control over the aileron surface position. Under this condition, full lateral stick inputs commanded full aileron deflection. In this way, lateral control was maintained using conventional pilot techniques without generating possible destablizing signals through the feedback path as roll effectiveness of the ailerons diminishes and yaw effectiveness increases.

2.4.3.2 Air-to-Air Combat - The control laws designed for this mission segment provided for rapid and precise maneuvering at all usable combat normal accelerations, the ability to rapidly minimize lateral offset errors, and the ability to operate at high AOA with command limiting to preclude loss of controlled flight. Two air-to-air combat modes were developed during the DFCS investigations; one was developed at MCAIR by modifying the Normal Mode and one was developed by General Electric (G.E.).

(a) MCAIR Air-to-Air Combat Mode (AACM)

Features

- Increased roll response
- Improved high AOA performance
- Reduced gust sensitivity
- Increased yaw damping

The AACM mode control laws were synthesized by modifying the Normal Mode control laws with the design objectives of providing faster responses and better air-to-air tracking capability using the effectiveness criteria of Section 2.3.2.

Modifications made to the Normal Mode longitudinal control laws were:

- A reduction in the prefilter time constant for faster response,
- Replacement of the normal acceleration feedback with an AOA feedback, and
- Elimination of the DLC capability.

The AOA feedback, with a gain based on the lift curve slope, approximated normal acceleration feedback at low aircraft angles-of-attack. At the higher angles-of-attack, where the slope of the aircraft lift curve decreases, the AOA feedback was greater than the normal acceleration feedback. In this way, the tendency to overrotate into dangerous angles-of-attack in tight turns was reduced by maintaining a constant stick force per degree AOA. The redundancy considerations for the use of AOA feedback are discussed in Section 2.15.6.

The modifications made to the Normal Mode lateral-directional control laws were:

- A reduction in the lateral-axis prefilter time-constant to provide quicker roll response,
- Alteration of the yaw rate feedback gain schedule so that the gain was increased at all values of Mach number to improve yaw damping and lateral aiming ability,
- Elimination of the lateral acceleration feedback gain in order to reduce the aircraft directional response to gusts, and
- Elimination of the Lateral Translation capability.

The overall effect was to achieve a quickening of aircraft response and better lateral air-to-air tracking. Figure 22 illustrates the roll quickening effect by comparing roll rate step commands for the AACM and the Normal Mode.

(b) G.E. Air Combat Mode (ACM)

Features

- Improved high AOA performance
- Increased roll response
- Planar Turn

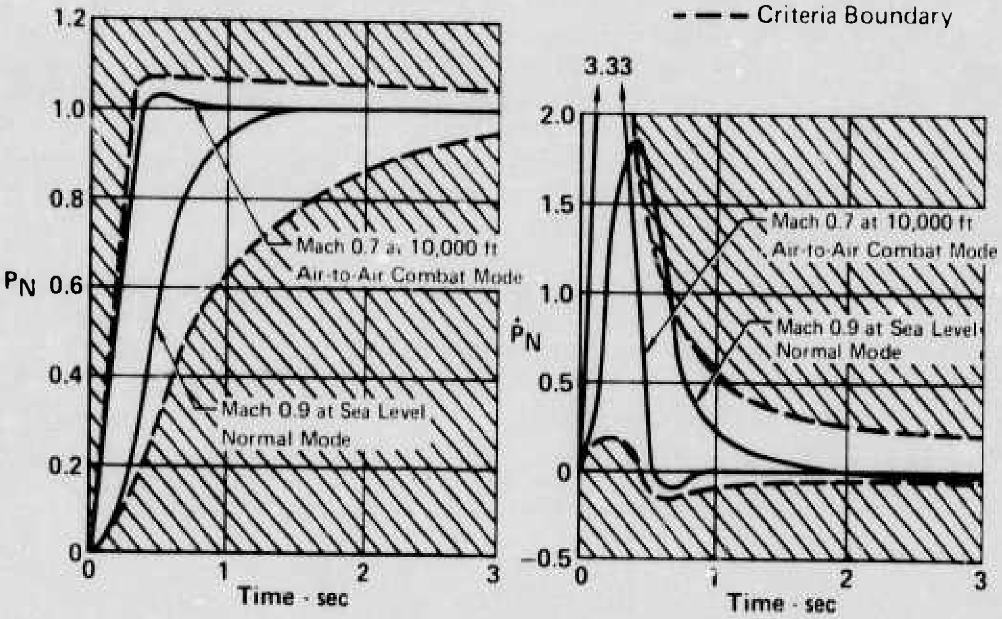


Figure 22
Normalized Roll Axis Response

- o Lateral stick - Controls plane of turn
- o Longitudinal stick - Controls rate of turn in the plane

  Longitudinal stick commands appropriate blend of roll and pitch so that turns are maintained in the plane selected through the lateral stick.

The ACM was designed by G.E. as a subcontractor participant in the Digital FCS program and is reported in Reference (12). The most unique feature of this mode was the pilot selectable Planar Turn option in which the lateral axis coupled to longitudinal stick inputs at load factors above two g to maintain a constant plane of turn. A complete description of the design of the ACM and the Planar Turn option are found in Reference (12).

2.4.3.3 Air-to-Ground Bombing Mode

Features

- o Roll stabilized about velocity vector
- o Neutral Speed Stability
- o Direct Lift capability
- o Flat Turn capability
- o Lateral Translation capability

Reference: 12. "Digital Flight Control System Study Final Report," ACS 10,713, General Electric Co., Binghamton, N.Y., October 1974.

The Air-to-Ground Bombing Mode was synthesized to provide precise control of the aircraft velocity vector using the effectiveness criteria of Section 2.3.2 so that good accuracy could be achieved. Modifications to the Normal Mode control laws were confined primarily to the lateral-directional axes, with the Normal Mode longitudinal control law requiring changes to the DLC networks only in order to optimize the DLC capability for vernier corrections of the velocity vector at the air-to-ground bombing flight conditions.

Modifications made to the Normal Mode lateral-directional control laws include:

- Addition of a gravity correction term to the yaw rate feedback path to produce aircraft roll rate stabilized around the velocity vector and yaw rate proportional to bank angle,
- Elimination of the integral control of sideslip and lateral acceleration,
- Elimination of the ARI crossfeed of roll rate error,
- Addition of the Flat Turn capability, and
- Modification of the Lateral Translation network.

All alterations to the lateral-directional control laws were made to provide the capability to roll about the aircraft velocity vector and to provide Lateral Translation and Flat Turn control.

The Flat Turn and Lateral Translation networks were derived by open loop decoupling techniques, so parameter scheduling was required for these features over the range of bombing flight conditions.

2.4.3.4 Air-to-Ground Gunnery Mode

Features

- Precise attitude tracking capability
- Reduced rotation due to gusts
- Roll stabilized about reticle
- Longitudinal axis reconfigures to include normal acceleration feedback above one g incremental
- Neutral Speed Stability
- Direct Lift capability
- Flat Turn capability
- Lateral Translation capability

The Air-to-Ground Gunnery Mode was designed using the effectiveness criteria of Section 2.3.2. The major requirement for the longitudinal axis is to provide good pitch control and keep uncommanded attitude excursions sufficiently small so as to provide good pointing accuracy. Good pitch control during air-to-ground tracking was provided through the use of a high gain pitch rate feedback control system. The normal acceleration feedback, included in the Normal Mode, was not used in the Air-to-Ground Gunnery Mode. The elimination of the normal acceleration feedback from the Air-to-Ground Gunnery Mode resulted in a stick-force-per-g gradient which is a function of aircraft velocity. This dependence on velocity caused stick lightening as velocity increased and could result in overrotation into stall during pullout maneuvers. This danger was eliminated by reconfiguring the longitudinal axis to include normal acceleration feedback above one g incremental load factor. Possible transients resulting from reconfiguration were minimized by adjusting the prefilter gain so that at a velocity of 750 ft/sec, the stick-force-per-g gradient of the Air-to-Ground Gunnery Mode was the same with and without the normal acceleration feedback. The DLC was retained in the Air-to-Ground Gunnery Mode to allow the nulling of small tracking errors without a change in pitch attitude.

Modifications made to the Normal Mode lateral-directional control laws include:

- Addition of a gravity term to the yaw rate feedback to produce roll rate stabilized around the gun reticle with turn rate proportional to bank angle,
- Addition of the Flat Turn capability, and
- Modification of the Lateral Translation network.

All alterations to the Normal Mode lateral-directional control laws were made to reduce rotation due to gusts and to provide the capability to roll about the gun reticle, and to provide Lateral Translation and Flat Turn control.

The Flat Turn and Lateral Translation networks were derived by open loop decoupling techniques, so parameter scheduling was required for these features over the range of air-to-ground gunnery flight conditions.

2.4.3.5 Manual Carrier Landing Mode (MCL)

Features

- Selectable automatic throttle holds 19 units AOA
- Direct Lift capability
- Direct Side Force capability
- Improved turn coordination

The MCL Mode was designed to comply with the handling qualities criteria of Section 2.4.2. This mode provided for pilot control of the flight path with thrust controlled by the automatic throttle. The control laws were also applicable to cases where the pilot controlled both flight path and thrust.

The power-approach configuration included full flaps, undrooped ailerons, and wing leading edge fixed slats compatible with full flap operation. The aircraft flew at 19 units AOA and an airspeed of 136 knots with 20% internal fuel. The automatic throttle system was set to maintain a trim AOA of 19 units. Bias setting of the horizontal canards was 5° leading edge down. Aircraft pitch control used inputs to the stabilator only. This was done to preserve the horizontal canard capability for DLC.

The DLC system for manual carrier landing was designed to meet the following objectives:

- Obtain 0.1 g capability,
- Minimize pitch attitude change,
- Obtain rapid response of change of altitude, and
- Retain adequate aileron authority for roll control.

Aircraft roll control for the MCL Mode used command inputs to the ailerons, spoilers, and rudder. Turn coordination was provided by roll crossfeed commands to the rudder and lateral acceleration feedback. The Lateral Translation control was designed to obtain rapid lateral acceleration onset with a peak acceleration of at least 0.05 g. The Lateral Translation networks were intended for use in the landing configuration and landing flight condition only, so variable networks were not necessary. Only limited aileron and rudder deflections were required to provide the Lateral Translation capability, and sufficient surface deflection capability was retained to provide unimpaired roll control.

2.4.3.6 Fixed Canards Mode

Features

- Neutral Speed Stability
- Coordinated turns
- Non-operable canards

The purpose of developing a Fixed Canards Mode was to provide adequate control capabilities (Category 2 of Reference (6)) in the pitch axis in the event of a failure in the canards control paths. In the event of a failure, the canards were automatically returned to and fixed at 5° leading edge down and would no longer perform control functions. The accompanying reduction in control power, without an accompanying increase in static stability, required that the Normal Mode longitudinal axis be modified slightly to maintain stability and controllability. No alterations were required for the Normal Mode lateral-directional axes other than disabling the DSF input paths.

The only modification to the Normal Mode required to provide adequate control was to fix the gain in the forward path.

2.4.3.7 DigiPACT Mode

Features

- General fighter control mode
- Digitized version of PACT analog system

The DigiPACT Mode was studied as an interim mode for the Digital FCS. The DigiPACT Mode consisted of a digital implementation of the existing analog SFCS-PACT control laws. These control laws were originally designed as a general-purpose fighter control law usable for all mission segments. The DigiPACT Mode was included to enable a comparison between a general-purpose control law and customized multimodes.

Other than the digital implementation of the control laws, the major difference between the analog SFCS-PACT and DigiPACT control laws was the location of the integration function in the longitudinal axis. The integration was required in the longitudinal axis to provide the NSS capability. The NSS was obtained in the analog control laws by utilizing a washout in the feedback signal around the secondary actuator. The DigiPACT Mode utilized an integration in the forward path.

2.4.3.8 Conclusion - Eight pilot-assist modes were developed and analyzed to assess the feasibility and desireability of incorporating into the Digital FCS customized multimodes which integrate aircraft control with mission demands. These modes were later evaluated and refined based on qualitative pilot opinion and quantitative workload and effectiveness data obtained during two man-in-the-loop simulations. The results of the simulation evaluation are presented in Sections 2.19, 2.20 and 3.3.

2.4.4 AUTOMATIC (PILOT-RELIEF) MODES

- Conventional Pilot-Relief Modes
    - Pitch Attitude Hold
    - Roll Attitude or Heading Hold
    - Preselect Heading
    - Altitude Hold
- Automatic Throttle
- Automatic Carrier Landing
- Automatic ILS
- Automatic Navigation
- Automatic Energy Management

The feasibility and desirability of incorporating into the ADP various mission-oriented pilot-relief modes were investigated. As a result, the above pilot-relief modes were developed to provide automatic control of flight path and other flight parameters to relieve pilot workload and improve mission effectivensss.

2.4.4.1 Conventional Pilot-Relief Modes

Features

- Holds altitude or pitch attitude existing at engagement
- Holds roll attitude or heading existing at engagement
- Captures and holds heading selected by the pilot

The Normal Mode was used as the inner loop for the Conventional Pilot-Relief Modes, with pitch attitude, roll attitude and heading obtained from an Inertial Navigation System and altitude from the Central Air Data Computer. The Pitch Attitude Hold, and Roll Attitude or Heading Hold Modes could be engaged any time the aircraft attitude was between ±70 degrees. Application of longitudinal or lateral stick force interrupted the Pitch Attitude Hold and Roll Attitude or Heading Hold Modes and returned control to the pilot via the Normal Mode. The subsequent release of the stick reengaged the mode at the new aircraft attitude. Control law logic based on roll attitude determined whether the system held roll attitude or heading. The aircraft automatically held the present heading if the roll attitude was less than 5 degrees, and held the present roll attitude if it was between 5 and 70 degrees.

The Preselect Heading Mode caused the aircraft to automatically fly to, capture, and hold a new heading selected on the CDC. Logic controlled the direction in which the aircraft turned to capture the new heading, with the maximum roll attitude limited during the turn.

The Altitude Hold Mode included an "up stabilator command" as a function of bank angle to provide improved altitude hold capability during turns. This command was based on the theoretical expression for the pitch rate gyro signal in a coordinated turn. Switching logic was provided to prevent Altitude Hold from being engaged unless the vertical velocity was less than 1000 ft/min to minimize the g engage forces.

2.4.4.2 Automatic Throttle Mode

Features

- Provides Mach hold in the up-and-away configuration
- Holds AOA at 19 units in the gear-down configuration
- Allows manual pilot override
- Automatically disengages when the pilot moves the throttle into the A/B range in the gear-down configuration
- Requires manual positioning into and out of the A/B range in the up-and-away configuration
- Cockpit throttle levers automatically follow engine cambox servo signals

The Automatic Throttle Mode provided Mach hold for the Normal Mode gear-up configuration, velocity and acceleration control for the Automatic Energy Management Mode, and Approach Power Compensation for the Normal, MCL, ACL, and Automatic ILS Modes. In the latter capacity, the Automatic Throttle Mode held 19 units AOA except when DLC was being used. The DLC produced an AOA reference change in the Automatic Throttle Mode that kept the Automatic Throttle from returning the aircraft to the 19 unit reference until DLC commands were removed. If the AOA reference were not changed, the automatic throttle would have washed out the effects of the DLC.

Control law logic was provided to keep the throttles from transitioning into or out of the A/B range without pilot intervention. A signal was displayed on the HUD indicating to the pilot whether the A/B or MIL power range was needed, and after the pilot made the transition, automatic thrust modulation was resumed. In the geardown configuration, any manual transition to the A/B range automatically disengaged the Automatic Throttle Mode. This mode was also disengaged by the actuation of either the gear or the speed brake.

2.4.4.3 Automatic Carrier Landing (ACL) Mode

Features

- Blended DLC and pitch attitude commands
- Blended DSF and roll attitude commands
- Deck Motion Compensation (DMC), or deck chasing, compensated for vertical deck motions of up to 16 ft peak-to-peak
- Reduced AOA excursions as compared to present F-4J ACLS

The DFCS ACL control laws included a blended DLC and pitch attitude command, and a blended DSF and roll attitude command not incorporated in present fleet ACL systems.

The use of the blended system for the "test case" aircraft resulted in:

- A reduction in the flight path angle time constant,
- A reduction in AOA changes to near zero in response to small pitch commands,
- A reduction in the required thrust change to maintain the reference AOA, and
- The elimination of the initial reversal of vertical and lateral acceleration at the aircraft cg at the onset of a command.

The blended DLC and DSF system required a different SPN-42 control law which was further modified by the addition of DMC. The DMC computations were accomplished in the simulated SPN-42 digital computer using data from the simulated shipboard accelerometer and gyro sensors. The system has shown good stability and flight path control under automatic carrier approach with a simulated vertical deck motion of as much as 16 ft peak-to-peak and a period of 10 seconds. During these simulations, the aircraft maintained a steady flight path down to 3000 ft from the touchdown point. Within 3000 ft, the system began deck chasing, allowing the hook to get in phase with the deck in less than 1/2 cycle and continued to follow the deck motion to touchdown. Because of the blended DLC, AOA excursions during the final deck chasing portion of the approach were about ±0.4 degrees. This compares with ±3.0 degrees for the present F-4J ACLS under the identical deck motion conditions.

2.4.4.4 Automatic Instrument Landing System (ILS) Mode

Features

- Capable of capturing the glide slope from above
- Holds altitude until the glide slope is intercepted when capturing the glide slope from below
- Remains well within the allowable 35 microamp overshoot of the glide slope centerline and the 37.5 microamp overshoot of the localizer centerline as specified in Reference (13)
- Uses the extensive computational capability of the Digital FCS to blend ILS signals with on-board roll attitude and normal acceleration signals permitting a higher gain system which results in good capture and tight flight path control

The control laws of the Automatic ILS Mode developed for the "test case" aircraft utilized the same attitude command loops used for the ACL Mode with the exception that the DLC and DSF blended system of the ACL Mode was not incorporated into the Automatic ILS Mode.

Reference: 13. MIL-F-9490D (Draft) Flight Control Systems-Design, Installation and Test of Piloted Aircraft, General Specification for, March 1974.

A vertical error from the glide slope beam was computed from the elevation angle error and aircraft altitude above touchdown. This signal was blended with aircraft normal acceleration and filtered to produce the pitch attitude command that directed the aircraft to the glide slope centerline. The ILS azimuth angle error was blended with aircraft roll attitude and filtered to produce the roll attitude command which steered the aircraft to the localizer beam centerline at a closure rate proportional to the azimuth error. Both the pitch and roll command signal paths include integral gains which eliminated system bias errors.

The filters on the attitude commands produced smooth and accurate path position and rate data, even when operating with a simulated ILS ground installation having a large amount of beam errors due to noise, beam bends, discontinuities, etc.

The automatic ILS configuration developed for the "test case" aircraft provided fully automatic Category I (Reference (9)) ILS approaches, commencing at a point outside the ILS outer marker when the aircraft was within the cockpit indicated limits of the ILS Localizer Signal. An altitude hold feature was incorporated to maintain the engage barometric altitude until intersection of the ILS glide slope beam. Automatic control continued until reaching the ILS middle marker, which occurred at an altitude of 200 ft. The system then disengaged, and the landing was completed by the pilot. System performance was well within the Reference (9) FAA requirements.

2.4.4.5 Automatic Navigation Modes

Features

- Acquired and tracked horizontal and vertical flight paths defined by the flight management computer
- Minimized overshoot during track capture maneuvers
- Smoothly transitioned from one flight path segment to another

An automatic vertical and lateral navigation capability was developed utilizing steering commands generated by the Collins ANS-70A computer and interfaced with aircraft pitch and roll attitude and the DFCS Normal Mode contol laws. Logic in the interface with the DFCS control laws provided for disengagement of the Automatic Navigation Modes with stick force, and system reconfiguration to the attitude hold modes.

2.4.4.6 Automatic Energy Management Mode

Features

- Minimum Time, Minimum Fuel, and Maximum Range energy ascent paths
- Maximum $\frac{L}{D}$ and Maximum Dynamic Pressure energy descent paths
- "Energy Look Ahead" implementation smooths flight paths and avoids high load factors

An automatic Energy Management (EM) Mode was designed for the "test case" aircraft with the capability of flying three basic optimum energy ascent flight paths and two energy descent paths. The capabilities provided were flexible enough for a variety of optimum mission segments to be flown automatically with pilot selection of the various available flight paths or with proper merging of target acquisition calculations and radar sensing. Studies of the energy characteristics of the "test case" aircraft revealed that optimum flight paths computed with a variable throttle setting were substantially the same as optimum flight paths computed with fixed throttle settings with very little penalty for using the fixed throttles. Since implementing optimum-path-following with variable throttle would have been more complex, optimum flight paths with fixed throttle were utilized in the system, although variable throttles were used for capturing end-point flight conditions and for maintaining proper velocities and accelerations in the high speed descents. Simplified all-digital simulations were used to check the EM system performance in the development stages.

The basic optimum-flight-path-capture method employed in the EM system was developed in earlier MCAIR EM studies. It is basically an "energy look-ahead" method which is described in Reference (14).

In implementing the control laws to follow the commanded flight paths, the flight path commands were converted to load factor commands. This conversion was used for two reasons:

- It was very convenient to convert the load factor feedback loop of the Normal Mode to a load factor control path by integrating load factor error, and
- It was desirable to place load factor limits on the flight path commands to avoid severe energy penalties from high load factor maneuvers. Thus, load factor commands were conveniently limited in the EM calculation prior to transmission to the control law calculation.

Digital logic was developed to perform the EM calculation, provide adequate limits on control loop input commands, perform switching among selected optimum flight paths, and coordinate flight path and throttle settings for capturing end-point flight conditions on or off the optimum paths. End-point captures were made by following approximately constant energy flight paths from the optimum flight paths. All path-following functions were developed using the basic look-ahead scheme described in Reference (14) or minor modifications of the scheme. The overall results of this mechanization was a system which follows optimum flight paths very well and which smooths discontinuities associated with theoretical optimum flight paths or intersections of flight paths.

2.4.4.7 Conclusion - Nine pilot-relief modes were developed and analyzed to assess the feasibility and desireability of incorporating into the Digital FCS customized control modes which provided automatic control of flight path and other flight parameters to reduce pilot workload. These pilot-relief modes were later evaluated and refined based on qualitative pilot opinion and quantitative workload data obtained during the Integrated Control Law and Display Simulation in which evaluation pilots flew individual mission segments and a complete mission scenario. The results of these evaluations are presented in Sections 2.20 and 3.3.

Reference: 14. Report in Writing: "Interface of Throttle/Energy Management Function with DAIS System for Fighter Aircraft", March 1975 (Report Number not yet available) Contract No. F33615-74-C-3103.

2.4.5 GAIN CHANGING - The design of the DFCS pilot-assist and pilot-relief mode control laws included gain changing to improve handling qualities as described in Section 2.3.2 and effectiveness as described in Section 2.4.2 over the range of design flight conditions. The five classifications of gain changing that were considered, in order of decreasing complexity, are:

- Self adaptive gain changing,
- Air data gain scheduling,
- Ordinary non-linearities (deadband, limits, etc.),
- Automatic gain switching with control mode or configuration changes, and
- Manual gain changing.

Self adaptive gain changing was considered as a possible method of providing gain adjustments to compensate for the wide range of aircraft dynamics encountered over the flight envelope. These gain changing schemes are generally active schemes since practical implementation of the aircraft dynamics identification process usually requires a periodic excitation of the airframe by an automatic control surface input device and measurements of the resulting response. Most of the available identification methods also require that a set of rather complex computations be performed constantly so that gain changes can be updated quickly to prevent degradation of stability margins and performance with rapid variations of flight conditions. Development of the multimode DFCS control laws revealed that gain changing requirements would be more numerous than in a single mode design if the full multimode capability was to be exploited. Self adaptive gain changing is generally an order of magnitude more complex than air data gain scheduling. This complexity coupled with some uncertainties about the applicability of current identification schemes for identifying unstable CCV aircraft dynamic parameters prompted design efforts to avoid adaptive gain changing if alternative air data scheduling would provide good system performance. It was found that air data scheduling of gains was a satisfactory method of gain changing for the multimode control laws. Therefore, the self adaptive methods are not recommended for the currently defined DFCS control system.

Table 2 is a preliminary list of the air data scheduled gains recommended for use in the DFCS control system. These gain changing elements are passive in that airframe dynamic excitation is not required for the gain changes to be effected. Aerodynamic or control parameters are measured passively, and the gain changes are determined using schedules which are stored in the flight control computers and which require relatively simple calculations for the desired gain determinations. The redundancy considerations for air data gain scheduling are discussed in Section 2.16.3. In addition to air data scheduling, ordinary nonlinearities and automatic gain switching with mode or configuration changes are recommended for performing adjustment of many gains not requiring continuous change with flight condition. Manual gain changing is reserved for use in the event of certain failures of air data scheduled gains.

Gain changing systems should be implemented with the redundancy of the control loops containing them. The gains associated with the Normal Mode must remain operational at all times for reasons of flight safety and for use for mission completion in the event of a failure of one of the specialized modes. It is planned that pilot selectable gain changing will be available for emergency use in the event that automatic gain changing equipment associated with the Normal Mode should fail.

Table 2
Air-Data Scheduled Gains

Forward Loop Gains[1]
Energy Management Load Factor Gain
Departure Preventer Gains
Yaw Rate and Sideslip Feedback Gains[1]
ARI Gains[1]
Lateral Translation and Flat Turn Network Gains
Automatic Navigation Outer Loop Gains

Note: 1. Gains Associated with the Normal Mode

Conclusion - Gain changing is required in the Digital FCS to improve handling qualities and effectiveness over the wide range of flight conditions and variety of mission segments flown. Efforts to simplify gain changing resulted in eliminating self-adaptive techniques and minimizing air data gain scheduling in favor of ordinary nonlinearities and gains changed automatically with configuration or mode changes. Manual gain changing was reserved for use only as a backup in the event of failure of certain air data scheduled gains as discussed in Section 2.16.3.

2.4.6 MODE COMPATIBILITY AND MODE SWITCHING - Implementation of the pilot-assist modes and the pilot-relief modes in the DFCS required defining mode compatibility and mode switching strategies. The criteria was to:

- Accomplish control law changes without objectionable transients,
- Simplify switching through integrated flight control mode and display switching, and
- Provide means for automatic and/or pilot selection of each mode in a manner compatible with safety and the use for which the mode was intended.

Figure 23 is the mode compatibility chart for the pilot-assist and pilot-relief modes. Switching between the modes was accomplished manually using the Computer and Display Controller (CDC) and switches on the throttles and SSC, or automatically if prescribed events occurred.

The following arrangement for manual mode selection of flight control modes was employed:

(a) All the pilot-assist and pilot-relief modes except ACL and Automatic ILS were engaged directly through the CDC.

(b) Selecting ACL or Automatic ILS on the CDC initiated the arming sequence of these modes. Once armed, ACL was engaged manually with the Data Link Coupler switch when the "CPR ON" command appeared on the HUD, and Automatic ILS was engaged automatically.

C = Compatible
N = Not Compatible

		Pilot-Assist Modes							Pilot-Relief Modes						
		DigiPACT	Fixed Canards	Normal	Air-to-Ground Gunnery	Air-to-Ground Bombing	Air-to-Air Combat	Manual Carrier Landing	Automatic Attitude Hold	Automatic Altitude Hold	Automatic Throttle	Automatic Carrier Landing	Automatic Energy Management	Automatic Vertical Navigation	Automatic Lateral Navigation
Pilot-Assist Modes	Fixed Canards	N													
	Normal	N	N												
	Air-to-Ground Gunnery	N	N	N											
	Air-to-Ground Bombing	N	N	N	N										
	Air-to-Air Combat	N	N	N	N	N									
	Manual Carrier Landing	N	N	N	N	N	N								
Pilot-Relief Modes	Automatic Attitude Hold	N	N	N	N	N	N	N							
	Automatic Altitude Hold	N	N	N	N	N	N	N	1						
	Automatic Throttle	N	N	C	C	C	C	C	C	C					
	Automatic Carrier Landing	N	N	N	N	N	N	N	N	3	4				
	Automatic Energy Management	N	N	N	N	N	N	N	1	N	4	N			
	Automatic Vertical Navigation	N	N	N	N	N	N	N	1	N	C	N	N		
	Automatic Lateral Navigation	N	N	N	N	N	N	N	2	C	C	N	C	C	
	Automatic ILS	N	N	N	N	N	N	N	N	3	C	N	N	N	N

Notes:
1. Automatic Altitude Hold, Automatic Energy Management and Automatic Vertical Navigation are compatible with Roll Attitude and Heading Hold and not compatible with Pitch Attitude Hold
2. Automatic Lateral Navigation is compatible with Pitch Attitude Hold but not compatible with Roll Attitude and Heading Hold
3. Automatic Altitude Hold can be used with ACL or Automatic ILS and will be automatically disengaged when the aircraft reaches the glide slope centerline
4. The Automatic Throttle is an integral part of the ACL and Automatic Energy Management Modes

Figure 23
Mode Compatibility Chart

(c) In addition to selection through the CDC, the Air-to-Air Mode was engaged through the Air-to-Air Mode Selection switch mounted on the throttle, and the Normal Mode was engaged through the Normal Flight Mode switch on the SSC. These additional means of mode selection made these modes available to the pilot without moving his hands.

A summary of the automatic mode switching implementation is presented in Table 3.

The mode switching strategies developed for switching from one mode to another produced smooth changes without objectionable transients during both the manual and automatic mode switching. In general, where feedback variables and command signals were engaged or disengaged, fade circuits were employed to eliminate any objectionable transients. The transition time of 2.5 seconds, associated with these fade circuits, was such that the pilot could compensate for any changes in stick force required to sustain the desired maneuver.

Conclusion - These switching strategies were incorporated into the control laws and evaluated by the simulation pilots during both the Control Law Simulation and the Integrated Control Law and Display Simulation. This method of reducing transients during mode transition was successfully flown in the SFCS flight test program to switch among the Normal, Electrical Back-Up and Mechanical Back-Up modes.

Table 3
Automatic Mode Switching Summary

Mode Disengaged	Mode Engaged	Switching Circumstances
Energy Management	Altitude Hold with Automatic Throttle	Either Desired Altitude or Desired Mach Number Acquired
Any Mode	ILS	ILS Armed and Aircraft within ± 0.7° of Glide Slope Centerline and ± 2.5° of Localizer Centerline
Pitch Attitude Hold	Normal Mode	Pitch Attitude Exceeds ± 70°
Roll Attitude Hold	Normal Mode	Roll Attitude Exceeds ± 70°
Roll Attitude Hold	Heading Hold	Roll Attitude Between −5° and +5°
Energy Management	Normal Mode	Application of Pitch Stick Force
Altitude Hold	Normal Mode	Application of Pitch Stick Force
ILS or ACL	Normal Mode	Application of Pitch or Roll Stick Force
Vertical Auto Nav	Pitch Altitude Hold	Application of Pitch Stick Force or Lateral Auto Nav Disengagement
Lateral Auto Nav	Roll Altitude Hold	Application of Roll Stick Force
Automatic Throttle	Manual Throttle	Lowering or Raising Gear or Actuation of the Speed Brake Switch or Afterburner Selected with Gear Down
ACL or Energy Management	Normal Mode	Automatic Throttle Disengagement

2.4.7 <u>SKEWED RATE SENSORS - PHASED TEST PROGRAM</u> - A program for incorporating into the DFCS test aircraft a set of angular rate gyro sensors, that are skewed with respect to the aircraft control axes, has been defined to enable installation and test of the skewed sensors in a phased flight test program. The potential advantage of skewed sensors is that each sensor can provide angular rate information for more than one control axis, with the result that fewer sensors would be required to achieve any given level of sensor redundancy. The phased program has been defined to initially use the existing rate gyros for vehicle control and concurrently record the output signals from the separate skewed gyros for subsequent analysis. After confidence is gained in the in-flight operation of the skewed sensors, these sensors would be employed for closed-loop control.

Task descriptions of the phased program for in-flight testing and operation of a set of skewed rate sensors are outlined below:

<u>Phase and Task Description</u>:

Phase I: Development and In-Flight Open Loop Evaluation

- Define installation locations for the skewed rate sensors.
- Detail design of aircraft and equipment modification for the in-flight selection of the skewed rate sensors and for simulated failure insertion on a per-axis basis.

- Perform analysis to define a suitable structural filter for each skewed rate sensor.

- Write the computer software programs for:

  - The structural filters, and

  - The redundancy management and coordinate equations which extract pitch rate, roll rate and yaw rate information from the skewed sensors and perform failure detection, failure isolation and system reconfiguration.

- Program the digital flight computers and conduct bench tests of the individual computers.

- Conduct a system bench test with the redundant computers married to the skewed rate sensors.

- Install the skewed rate sensor package and associated equipment into the aircraft.

- Conduct open and closed loop ground tests of the installed equipment.

- Conduct 5 flights with the skewed rate sensors operating off-line to evaluate:

  - The skewed rate sensor pitch rate, roll rate and yaw rate data,

  - The effectiveness of the structural filters, and

  - The failure detection, failure isolation and reconfiguration routines for pilot inserted simulated failures.

Phase II: Initial In-Flight Closed Loop Evaluation

- Modify structural filter design as necessary based on Phase I flight test results.

- Conduct 5 flights to evaluate the modified structural filters operating off-line.

- Conduct 5 flights during which the pilot selects on a per-axis basis between the skewed rate sensors and normal aircraft sensors for closed loop control in all flight control modes.

Phase III: Continued In-Flight Closed Loop Evaluation

- Conduct 5 flights using the skewed rate sensors exclusively throughout the flight envelope and in all flight control modes from takeoff to touchdown.

- Prepare a final report documenting the results of the skewed rate sensor test program.

Conclusion - A phased program was defined for the in-flight testing of a set of skewed rate sensors. This program, as presented, is contingent upon receiving from the Government the sensor configuration and redundancy management and coordinate equations required for implementing a set of skewed rate sensors into an aircraft for closed loop fly-by-wire control applications.

2.5 ELECTRICAL BACKUP (EBU)

For purposes of this analysis, EBU was defined as a mode which allows the pilot to command surface position rather than aircraft motion without the use of rate or acceleration feedbacks.

The three sound candidate configurations, which were evaluated in the reliability analysis reported in Section 2.17, all met the Statement of Work reliability goal without an EBU, although safety and reliability are improved if satisfactory performance can be provided by an EBU mechanization.

An EBU, as defined above, cannot control the pitch motion of an aircraft such as F-4 S/N 12200 with horizontal canards, when the basic airframe is unstable, and the control frequency is too high for the pilot to handle without pitch rate feedback. Accordingly, it is not planned that a pitch EBU will be used in the Digital FCS.

Safety is improved if an EBU is provided in the lateral-directional axes and it is anticipated that satisfactory lateral-directional handling qualities can be provided by an EBU (without rate feedback). Accordingly, an EBU may be provided as a reconfiguration capability of the Normal Mode for the lateral-directional axes.

2.6 PILOT INTERFACE

2.6.1 INTRODUCTION - An analysis was performed to determine the pilot interface with the Digital FCS. Each function identified was evaluated to determine how it would be performed. Information-processing, decision-making and action functions were allocated to the pilot, to a machine, or to a man-machine combination. Pilot tasks were assessed in terms of time-to-perform versus time available in each mission segment. Information gleaned from these analyses was used in the evaluations discussed below.

2.6.2 PROCEDURES AND TACTICS - The procedures and tactics identified were derived, in part, from current Air Force course materials used for pilot upgrading into advanced fighter aircraft. Modifications to existing procedures and tactics discussed herein are based on the evaluation of the aircraft aerodynamic control capability, dynamic simulation results, and pilot opinion data. Paragraph 2.6.2.1 below outlines the unique capabilities of the Digital FCS and the discussion in Paragraphs 2.6.2.2 through 2.6.2.7 describe the effects of the increased control capability, afforded by this system, on conventional pilot procedures and tactics.

2.6.2.1 Unique Flight Qualities of the DFCS Aircraft

- Aircraft handling qualities are not affected by cg variations over a wide range, such as might result from various weapon loads. The conventional aircraft becomes progressively more difficult to control and would be uncontrollable at aft cg's where no degradation would occur with the DFCS.
- Increased acceleration, turn rate, climb capability (better P_S, energy level)
  - Greatly reduced buffet at high angles of attack,
  - Wing rock at high angles-of-attack virtually eliminated, and
  - Control-limited load factor increased at supersonic speeds.
- Unique maneuvering capabilities for weapon delivery modes in that the aircraft can:
  - Gain or lose altitude in a constant pitch attitude,
  - Turn flat without rolling or side slipping, and
  - Translate laterally without rolling or changing heading.
- For air-to-ground gunnery, using conventional control inputs, the aircraft will roll about any selected aircraft axis thus eliminating the pendulum effect.
- For the Air Combat Mode, fuselage aiming provides a capability to maintain the aircraft flight path while changing the pitch attitude and/or heading.
- The Departure Preventer inhibits the aircraft from exceeding its structural limits. Sensors, such as angle-of-attack and acceleration, act as limiters on the aircraft control which prevent overstressing of the aircraft structure and prevent aircraft departures.

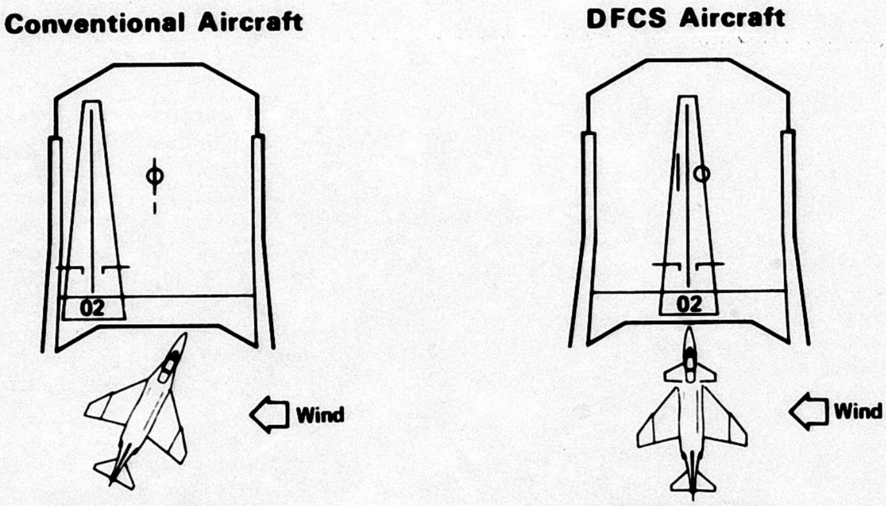
2.6.2.2 Aircraft and Tanker Hook-up - The current procedure requires the pilot to move to the contact position, when cleared by the boom operator, and stabilize the aircraft within two or three feet of the contact position. The air refueling director lights and refueling boom extension must be monitored while maintaining precise refueling position. In conventional fighter aircraft, the precise maneuvering of the receiving aircraft to the contact position requires a series of up or down pitch movements to match the tankers altitude and rudder induced rolls to match the tankers line of flight. Each of these flight changes entails a double attitude change (pitch up or down and level off, roll in and roll out) for altitude and lateral deviation corrections. With the DFCS, the pilot initially needs only to match the tanker's airspeed and position his aircraft within a cone of some appropriate dimensions below and behind the tanker. From this position he can control his airspeed with the throttle and translate up or down, left or right, using Direct Lift and Lateral Translation. The precise refueling contact point can be achieved without conventional pitch or roll inputs.

2.6.2.3 Precision Approach - An ILS approach assumes an airborne unit to determine aircraft deviation from a precision approach path and four ground station elements. These are the localizer, glide slope, marker beacons and approach lights. In current aircraft, the localizer signal is applied to the HSI course deviation bar, ADI localizer indicator, and the HUD integrated flight director. The glide slope signal is displayed on the ADI glide slope indicator and the HUD integrated flight director. The system receives signals from the marker beacon and illuminates the Beacon light and a comparable symbol on the HUD. The current approach procedure requires the pilot to select the proper localizer frequency and aurally verify the localizer identifier. He must set the published inbound ILS runway heading (course) in the COURSE window of the HSI. He must cross check the Instrument Approach Plate profile view for published minimums.

When established inbound on the localizer, he must setup approach configuration and maintain level flight until interception of the glide slope is indicated. The speed brake must then be extended and pitch and power adjusted as required. When the Beacon Lamp illuminates and the "BKN" symbol appears on the HUD indicating station passage, the controlling agency must be notified. The pilot then flies the on-course steering commands to the published decision height. One common difficulty confronting the pilot of a conventional aircraft while executing an ILS approach is maintaining proper course and position on the glide slope during descent.

The DFCS provides improved aircraft stability and requires less control activity for the pilot. Transition from level flight to the glide slope is simplified. When the pilot reduces power, the DFCS maintains the aircraft attitude, a negative flight path angle is established and the angle-of-attack is increased. Aircraft attitude changes, which typically occur with power changes and equipment extension; e.g., landing gear and speed brakes, are minimized. When the glide slope is captured and the required AOA established, tracking the course steering commands is enhanced. For manual approaches, adjustments in altitude and azimuth can be made using Direct Lift or Lateral Translation as necessary. Pitch and roll inputs are eliminated except where gross corrections may be required. The DFCS flight management concept eliminates the pilot's task of selecting ILS frequencies, setting the inbound ILS runway heading (course) in the course window of the HSI, and cross checking the published let-down plate. Proper display presentation is accomplished through pre-flight programming of the computer which assures automatic presentation of approach flight data. In the Auto ILS and Auto Throttle flight control modes, the aircraft is coupled with the ILS and is automatically controlled throughout the approach. The pilot needs only assume control at decision height and land the aircraft.

2.6.2.4 <u>Crosswind Landing</u> - In a conventional aircraft, crosswinds are compensated for by using the wing-low method, crabbing, or a combination of both. If the crab method is selected, the aircraft heading is aligned with the runway just prior to touchdown. The wing-low method, depending on the mechanization of the flight control system, will likely require overpowering the aileron rudder interconnect (ARI) with the rudder or disengaging the ARI by pulling the circuit breaker. The DFCS eliminates the requirement for employing either of these techniques. Once proper runway alignment has been achieved, a normal descent and touchdown can be made using only Lateral Translation (direct side force) as necessary to compensate for the crosswind. The problems inherent with aircraft slip or crab during the approach are eliminated. An illustration depicting a crosswind landing with and without Lateral Translation capability is presented in Figure 24.



Conventional Aircraft

DFCS Aircraft

CRAB or SLIP Required to Correct for Wind Drift

Direct Side Force Compensates for Wind Drift

Pilot Comments:

- **Very Effective for Aligning Aircraft Longitudinal Axis with Runway Heading and Eliminating Aircraft Drift**

Figure 24
Effect of Lateral Translation Capability
Landing Segment

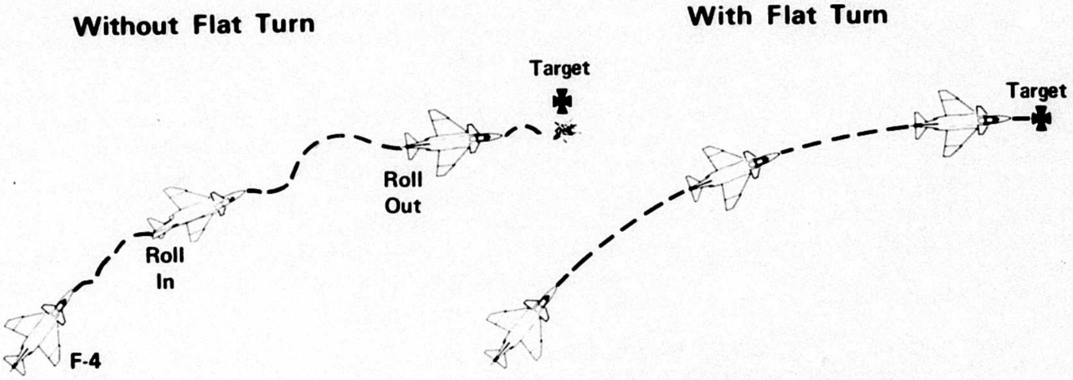
2.6.2.5 <u>Navigation</u> - Current fighter aircraft navigation capabilities generally include ILS, TACAN, and an Inertial Navigation System (INS). The ILS has been discussed previously under "Precision Approach". Current TACAN procedures require the pilot to sequentially select the individual TACAN frequencies, aurally verify the station identifier, select the desired radial, and fly the flight plan (normally displayed on the pilot's kneeboard) from data displayed (bearing and distance, bank command, and course deviation) on the HUD, ADI and HSI. The aircraft is flown manually, however, auto flight control features such as attitude hold and altitude hold may be used on individual course legs. The INS is a fully automatic three dimensional navigation system, which provides the primary attitude reference, and displays a continuous present position in latitude and longitude. Data for destinations, air-to-ground targets, or aircraft present position can be inserted in the navigation control indicator. The pilot, having selected and inserted a destination and the NAV Steer Mode, receives steering data from the HUD, ADI and HSI to the destination selected. Upon reaching the destination, he must manually select the next destination. Navigation information will again be furnished to the pilot through the aforementioned displays. Again, the aircraft is flown manually; however, auto flight control features (attitude and altitude hold) may be used during the flight.

The DFCS flight management implementation provides for position fixing, flight plan management, steering computations, point-to-point navigation, airport procedures and other informtion such as electronic warfare data required to support tactical fighter operations. It also provides a fully automatic three dimensional area navigation system capable of flying directly between any two points as well as on airways, SID's, STAR's, and RNAV routes. The flight management computer, rather than the pilot, performs sensor management, such as frequency selections and initialization. The DFCS flight management implementation provides for external loading of the flight plan which can then be called up on appropriate displays. The point of origin and destination and all intervening waypoints, complete with specified altitudes, are displayed on the CDC. Course lines for each leg are displayed on a Multi-Functional Display (MFD II). Having constructed the flight plan, the pilot, after takeoff, can engage the Auto Lat Nav and Auto Vert Nav flight control modes, which automatically fly the lateral and vertical profile of the designated flight plan. Other options, such as offset course guidance of up to ±40 miles, and automatically executed holding patterns, are also available and can be integrated with the regular flight plan. These capabilities greatly reduce the navigation workload of the pilot, such as selecting pertinent TACAN frequencies; and resolves most of the mental calculations, such as time and distance to next waypoint, normally required for the accomplishment of the total mission.

When flying the flight management system manually, the CDC and Map Display are operated in the same manner and present the same data as previously discussed.

2.6.2.6 Air-to-Ground Gunnery and Bombing - The key to a successful air-to-ground delivery is the pilot's ability to fly his aircraft to meet a set of predetermined release conditions, e.g., airspeed, altitude, and dive angle. Current procedures require the pilot to select the proper reticle depression angle, visually acquire the target, and maneuver the aircraft to approach the run-in heading from a 90° position. After establishing the airspeed, he must roll into the target allowing for a crosswind and lower the aircraft nose below the horizon after 30° into the turn. Roll-out should be made so that the dive angle is slightly steeper than necessary to ensure the reticle is below the target. Cross-check of the displays must be accomplished while maintaining track and airspeed. Release or firing may be initiated when slant range, dive angle, airspeed, and sight reticle on the target are simultaneously achieved. Rapid, accurate solution of the target tracking problem is the primary task of the fighter pilot in the air-to-ground flight environment. The pilot also has the option to fly the AUTO mode, which is a fully computed automatic weapon release mode. The aircraft is flown to position the reticle on the target. The designator controller is depressed designating the target and automatically switching to the AUTO mode. The target designator box, azimuth and elevation steering lines, time-to-go, and the velocity vector are displayed as primary symbols in this mode. The target designator box remains positioned on the target, and any designation error may be corrected by repositioning the designator. The major task in this mode is nulling the azimuth steering error by flying the velocity vector to coincide with the azimuth steering line.

The pilot, flying the DFCS, needs only to align the aircraft with the approximate target position, and then accomplish precise alignment and target tracking through Flat Turning, Lateral Translation, and Direct Lift. The Flat Turn capability is available to the pilot through the rudder pedals and Lateral Translation and Direct Lift through the controller on the side stick. The normal DFCS technique after roll-in on the target is to solve azimuth displacement using the Flat Turn capability and eliminate wind drift with Lateral Translation. Illustrations depicting use of the Flat Turn and Lateral Translation capabilities in air-to-ground mission segments are shown in Figures 25 and 26 respectively. Vertical corrections would be accomplished with Direct Lift or pitch inputs. This technique eliminates the need for conventional rolling of the aircraft with its resultant pendulum effects. However, when larger corrections are required, the DFCS aircraft can be rolled about any selected aircraft axis, e.g., the reticle depression angle, which effectively eliminates the pendulum effect.



Heading Correction Requires Repeated Right and Left Lateral Stick Inputs

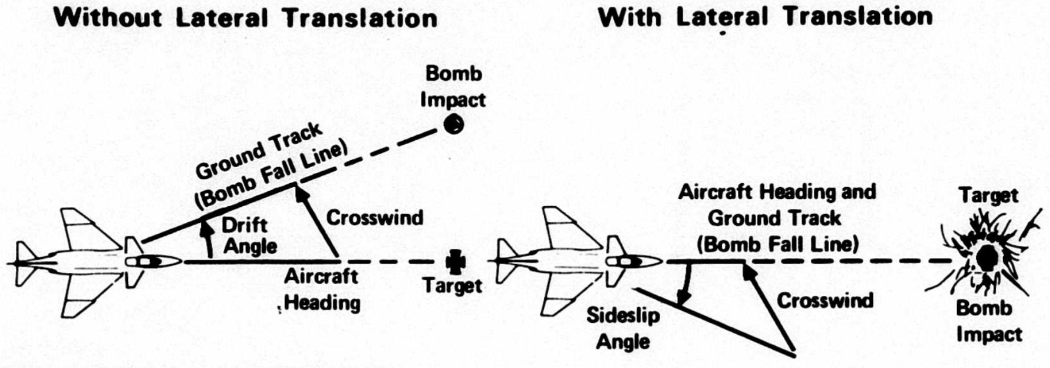
Heading Correction Requires Only Rudder Pedal Input in the Direction of the Turn

Pilot Comments:

- **Very Effective for Small Heading Corrections in Air-to-Ground Segments.**
- **The Use of Rudder Pedals Provided a Natural Means for Flat Turn Control.**

Figure 25
Effect of Flat Turn Capability

2.6.2.7 Air-to-Air Combat - Air combat involves the use of maneuvers which are divided into offensive and defensive categories. Basic offensive maneuvers include the high and low yo-yo, lag pursuit, lag roll and barrel roll attacks. The number of basic defensive maneuvers is somewhat greater and includes the split, break, hard turn, roll away, high-g barrel roll, spiral, flat and rolling scissors, and vertical reversal. This inventory of maneuvers is used by the fighter pilot in the combat environment to complete a successful attack on an enemy aircraft or to extract himself from a defensive situation with the enemy to his rear. How well he accomplishes the specific task at hand is directly related to his proficiency as a pilot and the flight characteristics of his particular aircraft.


Without Lateral Translation

With Lateral Translation

Note: The illustrations neglect ballistic drag effects

Pilot Comments:

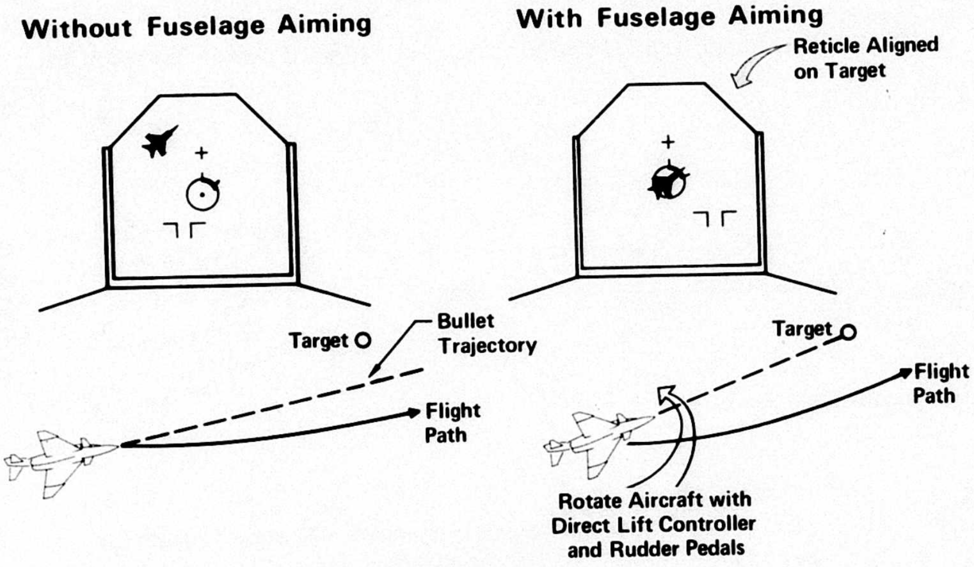
- **Very Effective for Aligning the Aircraft Longitudinal Axis with the Ground Track in Steady Crosswinds**
- **A Displacement Type Controller is Preferred in Lieu of a Force Controller for Lateral Translation**

Figure 26
Effect of Lateral Translation Capability
Bombing Segment

The aircraft control responses for the DFCS have been tailored to the requirements of the air combat situation. Increased acceleration, turn rate, and climb capability have been achieved through the installation of horizontal canards and wing slats which have reduced maneuvering drag, and increased lift. This effectively produces a better energy level for maneuvering flight. At high angles-of-attack, buffet is greatly reduced, and wing rock is virtually eliminated. The "g" capability of the aircraft is increased at supersonic speeds. The integration of a Departure Preventer allows the pilot to concentrate fully on the aircraft against which he is maneuvering and minimizes the requirement to monitor continually the airspeed, angle-of-attack and g-indicator. These increased capabilities allow the pilot to exploit the advantages derived from the typical air combat maneuvers.

Lateral and Vertical Fuselage Aiming will be possible in the DFCS through the use of the rudder pedals and the direct lift controller in the Air Combat Mode. This capability will allow the pilot to rotate the aircraft fuselage, which changes the aircraft pitch attitude and heading, but maintains the direction of the existing velocity vector. The technique allows the pilot to align his aircraft gun with the target without changing the aircraft flight path. Fuselage Aiming can effect a gun solution not normally attainable from certain flight situations. An illustration depicting the use of fuselage aiming in air-to-air combat is presented in Figure 27.

2.6.2.8 Conclusion - An evaluation of pilot procedures and tactics, in terms of the unique flight qualities of the DFCS aircraft and its integrated flight management system, indicates a definite increase in weapon system capability. The high degree of flight automation and display integration simplified pilot tasks and enhances his ability to perform specific procedures and tactics. These increased capabilities should provide improved weapon delivery effectiveness without increased workload.



Pilot Comments:

- **Fuselage Aiming Should be Provided for Air-to-Air Combat**

Figure 27
Fuselage Aiming

2.6.3 DFCS EMERGENCY PROCEDURES - An evaluation was conducted to determine the necessity for developing emergency procedures with the current DFCS design concepts. The following rationale has been established:

2.6.3.1 Flight Control - The flight control system will be designed to automatically reconfigure when failures occur. Therefore, little or no emergency pilot procedures will be required for flight control for first failures. An example of what might be done after multiple failures is shown in Figure 28.

2.6.3.2 Displays and Controllers - Essential flight data are presented redundantly on the HUD and MFD I. It is also planned that the essential flight parameters will be hard wired to the HUD and MFD I. This will provide for continuous flight data in the event of either display or computer failure. The CDC and flight management computer with the MFD II provide the additional flight plan management data. This capability should provide sufficient redundancy to circumvent the effects of a display or computer failure and make specific emergency pilot procedures unnecessary for first failure of displays and/or controllers. Failure annunciation however may be desirable.

2.6.3.3 Electrical Power - It is planned that battery electrical power will be supplied to both the flight control system and displays in the event of aircraft generator failure. This will provide for continued operation for some specified period of time and removes the need for a specific emergency procedure. Failure annunciation, however may be desirable.

2.6.3.4 Conclusion - The evaluation indicated that few emergency procedures need be developed for the current DFCS design concepts.

2.6.4 DEDICATED VERSUS TIME-SHARED DISPLAYS AND CONTROLLERS - Each mission function was analyzed to determine its information requirements. Task identification was accomplished by further subdivision of each function. The results of these studies were used to establish the displays information and controller capabilities needed to support each of the mission functions.

The display information was subsequently assigned to specific displays, i.e., HUD, MFD I, MFD II, and/or CDC. These assignments resulted in the identification of opportunities for time-sharing of information on each of the displays. An example of the time-sharing of display information is presented in Table 4 by the changes of display information for the functions of the radar missile attack segment.

Table 4
Example of Time-Sharing of Display Information

Segment	Function	HUD	MFD- I	MFD- I Alternate	MFD- II
Radar Missile Attack	Navigate to Target	Flight Director Airspeed Altitude Attitude Heading Velocity Vector Mach Flight Control Mode Side Slip Angle Lateral Acceleration Gun Cross	Radar Display (A/A) Airspeed Altitude Attitude GS and TAS Mach Flight Control Mode Antenna Azimuth Scale and Marker Antenna Elevation Scale and Marker Radar Range Scale Radar Grid Lines Target Display Target Designator	Flight Director Aircraft Reference Airspeed Altitude Attitude Heading Mach Flight Control Mode Side Slip Angle Lateral Acceleration	Aircraft Symbol Flight Plan Waypoints Range (80 NM) Heading Lubber Line Tactical Data (SAM, AAA, and AA Threat Data) Range Marks
	Select Pilot Assist Mode (A/A Combat MRM)	Same as Above + Weapon Type and Quantity + G Readout –Flight Director	Same as Above + G Raadout	Same as Above	Same as Above
	Detect and Identify Target	Same as Above	Same as Above + Radar Target + IFF Target Data – IFF Target Data	Same as Above	Same as Above
	Perform Radar Lock-On	Same as Above + ASE + Target Range + Launch Limits + Steering Dot + Radar Range Rate + Target Designator Box + Missile FOV	Same as Above + ASE + Target Range + Target Altitude Delta + Steering Dot + Radar Range Rate + Launch Limits – Target Designator	Same as Above	Same as Above

The controller capabilities needed to support each of the mission functions were assigned to the specific controllers, i.e., side-stick, throttles, and CDC. These assignments, which were accomplished using MIL-STD-203E as a guide, resulted in the identification of opportunities for time-sharing of the capabilities on each of the controllers. Three controller mounted switches, where time sharing was utilized are as follows:

- Gunsight Stiffen or Missile Reject Switch (Throttle) - Changes function to match selected flight control mode.

- Auto Acquisition Switch or Inflight Refueling Probe Disengage (Throttle) - Changes function to match radar power switch position, i.e., refuel probe disengage when radar is in OFF or STBY and auto acquisition with radar in operation.

- Nose Gear Steering or SRM Uncage (Side Stick Controller) - Change function according to weight on wheels switch open or closed.

In addition, the keys of the computer and display controller are time shared as discused in Reference (15).

Conclusions

Military pilots evaluated the time-sharing aspects of the DFCS cockpit arrangement during the static Displays and Controllers Evaluations and the dynamic Integrated Control Law and Display Simulation. Results of these evaluations are presented in Section 3.0. Time-sharing concepts were readily accepted by the pilots and they expressed the opinion that these time-sharing innovations of displays and controllers would reduce workload and enhance weapon system management.

Reference: 15. Digital FCS Study Final Report, 523-0766085-00111M, Collins Avionics Division, Rockwell Internationl, Cedar Rapids, Iowa. 15 February 1975

2.7 DISPLAYS AND CONTROLLERS DEVELOPMENT

2.7.1 INTRODUCTION - Display and controller analyses were performed to help develop and evaluate crew-system concepts for displays and controllers. The results of the analyses were used to help design the configurations for the design aid and simulation. The following objectives were considered in the analyses and design:

- Enhancing the operation of the Digital FCS,
- Permitting the pilot to behave as a mission-oriented manager rather than a subsystem operator,
- Utilizing the pilot's decision-making capability within acceptable workload levels, and
- Accomplishing all of the above without increasing pilot workload.

The results from the Pilot Interface Analysis (Section 2.6) along with the knowledge gained through the review of related, previously accomplished, programs such as the IIPACS program, References (16), (17), (18), and (19), the HAC program, Reference (19), and the AIMIS program were utilized to develop initial crew-system concepts discussed in Section 2.7.2.

These crew-system concepts combined with the results from the Mission Scenario Analysis; Air Force, Navy and MCAIR Displays and Controllers Coordination Meetings; drawing layouts; and three dimensional design aids were used to establish the candidate display and controller arrangements.

Displays analyses and controllers analyses are discussed in Sections 2.7.3 and 2.7.4, respectively.

References:

16. Zipoy, D.R., and Premselaar, S.J., "Advanced Integrated Fighter Cockpit Study," Technical Report AFFDL-TR-71-57. Wright-Patterson AFB, Ohio. June 1971.

17. Zipoy, D.R., et al, "Integrated Information Presentation and Control System Study, Volume I System Development Concepts" Technical Report AFFDL-TR-70-79. Wright-Patterson AFB, Ohio. August 1970.

18. Zipoy, D.R., et al, "Integrated Information Presentation and Control System Study, Volume II, System Analysis," Technical Report AFFDL-TR-70-79. Wright-Patterson AFB, Ohio. August 1970.

19. Premselaar, S.J., et al, "Integrated Information Presentation and Control System Study, Volume III Degraded Mode Analysis," Technical Report AFFDL-TR-70-79. Wright-Patterson AFB, Ohio. June 1971.

20. Sinnett, J.M., Asiala, C.F., "Advanced Fighter Concepts Incorporating High Acceleration Cockpits; Volume IV-Pilot Performance Analyses," Technical Report AMRL-TR-72-116. Wright-Patterson AFB, Ohio. July 1973.

2.7.2 CREW-SYSTEM CONCEPTS - Analysis and design were performed to establish crew-system concepts for the Digital FCS cockpit geometry, lighting and lighting control, and locations of proposed controllers and displays. Cockpit designs prepared for use in engineering evaluations, workload analyses, and the design aid and simulator construction were modified and refined as the Digital FCS Study progressed. These designs were used in part to formulate the recommended ADP configuration.

The cockpit geometry for the Digital FCS design was based on the overall dimensions of the designated F-4 test aircraft. The seat, console location, canopy sill height, windshield bow, and fuselage structure in the cockpit are representative of a typical F-4. However, consoles, instrument panels, displays, and controllers have been located to provide the most acceptable access and ease of operation. The overall arrangement was designed to be generally compatible with the High Acceleration Cockpit (HAC) concept, Reference (20).

Lighting and lighting control for advanced electronic displays is recognized as a critical area for design consideration. The Digital FCS display and controller concept provides for manual control of cockpit and specific component lighting. In addition, electronic displays such as the HUD and MFD's are provided with individual manual and automatic display intensity controls to compensate for varying ambient light conditions. Lighting and lighting control concepts are not, however, subject to practical analysis and verification by static design aids and simulation of the type done as a part of the Digital FCS Study.

Initially, designs were prepared to determine candidate display and controller arrangement, location, and configuration. Numerous arrangements were defined in sketch form. These arrangements were subjectively evaluated by MCAIR design engineering, human engineering, and pilot personnel. Critiques and suggestions were made by the Air Force and Navy project office personnel during various coordination meetings. Several of these arrangements were then refined by more detailed design work. Air Force and Navy standards for human engineering design criteria and pilot anthropometric data were used as criteria for the design layouts. The major controllers, i.e., the side stick, rudder pedals, throttle, and Computer and Display Controller (CDC), were designed to accommodate the 5th through 95th percentile pilots.

Conclusions

Cockpit arrangements generally compatible with the HAC concept were designed and refined for subsequent use in engineering evaluations, workload analyses, and construction of the design aid and simulator. The resulting arrangement was used in part to formulate the recommended ADP configuration.

2.7.3 DISPLAYS ANALYSES - Analyses were conducted to define advanced cockpit displays which offer possible reductions in pilot workload, and improvements in weapon system management over conventional displays.

Early in the display development, an arrangement was established which formed a basis for the specific analysis topics. First, it was decided that a Head-Up Display (HUD) was a basic requirement. It was also decided that two separate head-down CRT displays were desirable to provide the pertinent radar, EO, EADI, and EHSI information. One CRT would primarily present vertical situation information and is designated Multi-Function Display I (MFD I). The other CRT would primarily present horizontal situation information and is designated MFD II.

Specific topics which were included in the analyses are:

- Utilization of advanced Digital FCS control laws for display information,
- Levels of display redundancy required for Digital FCS implementation,
- Considerations of dedicated vs time-shared displays,
- Pilot-computer-display interface,
- Display symbology and formats,
- Considerations of various mission-oriented displays,
- Priority management system for the displays,
- Considerations of data processing functions accomplished in separate symbol generators,
- Considerations of integrating energy management parameters with conventional flight control parameters,
- Computer-generated advisory information in discrete data and numeric form,
- Advisories for preflight and in-flight failure information, and
- Annunciator displays to provide advisory status and readout of selected Digital FCS functions.

2.7.3.1 Utilization of Advanced Control Laws for Display Information - Analysis and simulation results indicate that the display information should be mission oriented, i.e., only the information required for a mission segment should be presented while that segment is being flown. Since the multimode control laws are also mission oriented, it may be said that the displays are directly related to the control laws. However, with the following exceptions, little display information can be derived directly from the control law computations:

- Energy management desired profiles in the Mach and altitude plane,
- Pitch and roll steering commands for auto navigation, ILS, ACL and energy management, and
- Alpha-numeric indicating flight control mode selected.

The control law computations were utilized to derive information for the above parameters during the Integrated Control Law and Display Simulation.

2.7.3.2 Levels of Display Redundancy Required - Display redundancy has been discussed as part of other related studies. Essential flight data can be and have been presented redundantly on the HUD and MFD I as a part of the weapon delivery and sensor displays. The MFD I display format incorporates airspeed, altitude and aircraft attitude with or without the Radar, Electro-Optical, or Infra-Red sensor displays. Heading information is displayed redundantly on the HUD and MFD II and is incorporated in the MFD I flight information display format. It also is planned that essential flight data will be hard wired to the HUD and MFD I. This redundancy will provide continuous flight data in the event of failure of either a display or a flight management computer. Back-up electrical power will be supplied to the displays, as well as the FCS, in the event of failure of normal electrical power. The redundant display of essential flight data has been demonstrated by the Integrated Control Law and Display Simulation.

2.7.3.3 Considerations of Dedicated Versus Time-Shared Displays - The analysis of dedicated versus time-shared displays is discussed under Section 2.6.4.

2.7.3.4 Pilot-Computer-Display Interface - Analysis and simulation indicate that simplified pilot access to displays, simultaneously with flight control mode selection through switches on the primary controllers and/or the CDC, is effective in reducing pilot workload as shown in Section 2.20. Also, the option for selection of display presentations independent of the flight control mode selected is desirable.

2.7.3.5 Display Symbology and Formats - Analyses were performed to define symbology and formats to be used in the flight control mode related displays which enhance the operation of the Digital FCS. The symbology developed is designed to present clear and concise flight, attack, take-off and landing information to the pilot. The display's information content and ease of comprehension were designed to reduce pilot workload and improve mission effectiveness as defined in Section 2.3.

Initially, a search was made of various specifications and reports concerning electronic displays. The information acquired was combined to form baseline symbology and formats. Additional display symbology and formats were provided by the Air Force and Navy Program Office. Several examples of symbols and formats were assembled into a package of "Paired Comparisons" and "Information Requirements Questionnaire". The package was then evaluated by Air Force and Navy test pilots to obtain their preference of specific symbols and formats to be displayed during various flight segments. The results of the evaluation were assembled and reviewed by Air Force, Navy and MCAIR representatives during a coordination meeting. This review resulted in agreement on the initial set of symbology and formats to be evaluated during dynamic simulations.

During the Integrated Control Law and Display Simulation evaluation, pilots made additional recommendations for symbology and format changes; see Section 3.3.3.

2.7.3.6 Consideration of Various Mission Oriented Displays - Analysis indicates that generally, only the display information required for a mission segment should be presented while that segment is being flown. Therefore, appropriate formats were developed with the required information to provide presentations which are simultaneously displayed when a flight control mode is selected and automatically displayed when other discrete events occur, e.g., landing gear position change, radar status change or faults. The preceding philosphy was confirmed by the simulations; see Section 3.3.3.

2.7.3.7 Priority Management System for the Displays - A priority management system for display content and format was developed which provides a display presentation appropriate to the flight control mode selected and a discrete event, e.g., gear down, weapon status, range of a target. During the simulation, radar presentations were designated as first priority information for the MFD I. Subsequent pilot evaluations indicated that when the normal flight control mode is selected, they preferred the MFD I priority presentation to be the EADI. The system also provided for the automatic display of an appropriate format and/or high priority advisory information when pertinent, e.g., control system faults or a tactical threat.

2.7.3.8 Considerations of Data Processing Functions Accomplished in Separate Symbol Generators - Display data processing functions, normally included in symbol generators, are as follows:

- Input/Output circuitry for interface with the display computer and/or direct interface with external sensors,
- Data memory which consists of random access memory for buffered storage of input data,
- Central Processor Unit (CPU) which controls data and program addressing, sequencing, and processing for input to the waveform generator,
- Program memory, usually PROM or ROM, which contains the entire symbol calculation instruction set, and
- Waveform generator, which contains an alphanumeric generator, and a line and circle generator. The waveform generator converts digital data from the CPU into analog waveforms with blanking pulses for presentation on the display units.

Traditionally, these functions have been included in a single, dedicated symbol generator for each display unit; however, since the functions are basically identical, it is reasonable to consider time sharing and relocating some of these functions such that a single symbol generator can be used to drive two display units. With minimum symbol requirements, it is feasible to provide appropriate switching and multiplexing enabling a single symbol generator to drive several displays. This appears cost-effective, but the symbol generator then becomes a single point failure and the cost advantages may be lost when redundancy is necessary for reliability considerations. Another problem is that several typical HUD display modes require continuous data processing attention as the symbol calculation and writing times nearly approach the symbol refresh period. In short, the HUD uses the full symbol generator cycle time capacity and leaves no time for sharing symbol generation time with other displays. The problem results primarily from the fact that HUDs are restricted to slow writing rates, e.g., 3000 IPS, in order to achieve the necessary high luminance output.

One approach for integrating and time-sharing symbol generation functions is to move the waveform generators from the symbol generators into the display units and then drive the display units directly from the display computer. Analyses indicate that this approach tends to overburden the display computer both in terms of memory and cycle time requirements and, as a result, would compromise the primary computer functions.

Another possible alternative is to include the waveform generators within each display unit, with all displays driven by a single data processor which is in turn driven by the display computer. This takes the load off the display computer and allows maximum time-sharing of common symbol-generation hardware. In this approach the processor initiates a symbol in one display; while that waveform generator is drawing, the processor initiates the second display and so on. As mentioned above, the problem with this method is that the processor becomes a single point failure for the entire display system and a redundant processor would most likely be required.

The most cost-effective approach to symbol generation is a concept that includes a dedicated symbol generator for the time-consuming HUD and a single data processor for driving both MFD I and MFD II, which include their own waveform generators. In this manner, adequate flight information remains in the event of failure of either symbol generator.

2.7.3.9 Considerations of Integrating Energy Management Parameters with Conventional Flight Control Paramaters - Consideration was given to integrating energy management parameters into the displays along with the conventional flight control parameters. Symbology and formats were developed for energy management presentations to be displayed on the HUD and MFD I. MFD I displays were adapted from the Beyond-Visual-Range Altitude-Mach displays described in Reference (21). EM displays were generated on the HUD by adding altitude and Mach command indices to the altitude and Mach scales.

2.7.3.10 Computer Generated Advisory Information in Discrete Data and Numeric Form - During display format development an analysis was performed to identify the aircraft flight parameters and system advisories which should be displayed on the HUD and the MFDs. Alphanumeric windows are provided and allocated to specific data, e.g., weapon status, aircraft "g", Mach and waypoint data.

2.7.3.11 Advisories for Preflight and Inflight Failure Information - Provisions have been made to present failure information on the CDC when a failure is detected. An example of such information is shown in Figure 28. An appropriate warning will appear on the HUD and MFD I to advise the pilot to check the CDC.

2.7.3.12 Annunciator Displays to Provide Advisory Status and Readout of Selected DFCS Functions - Flight control mode advisory is provided alphanumerically on the HUD and MFD I, e.g., NORM, A/G. The CDC provides a number of other advisory readouts as discussed in Paragraph 2.7.4.5.

2.7.3.13 Conclusions - The major conclusions resulting from the displays analyses are:

- o Displays would consist of a HUD, MFD I, and MFD II;
- o The HUD would be the primary flight instrument for most flight situations;
- o The CDC would be used for simplified pilot-to-computer communication;
- o Essential flight data would be hard wired and presented redundantly on the HUD and MFD I;
- o Sensor presentations, e.g., Radar and EO, would be displayed on MFD I or MFD II;
- o Backup electrical power would be supplied;
- o Normally only information required for a mission segment would be displayed while that segment was being flown;

Reference: 21. Pruitt, V. R., "Energy Management Display System for a Tactical Fighter," Technical Report AFFDL-TR-73-38. Wright-Patterson AFB, Ohio. April, 1973.

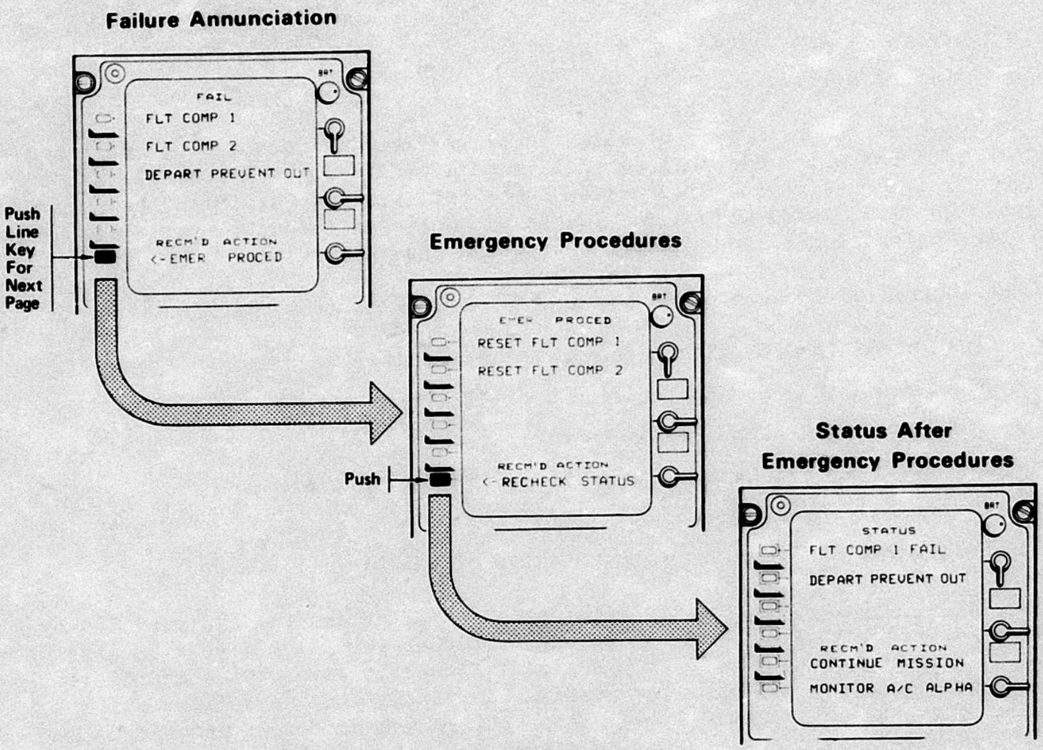


Figure 28
Emergency Procedures - Flight Control System Failure

- o Pertinent high priority threat and fault information would be automatically displayed when appropriate;
- o A dedicated symbol generator would be used for the HUD and a single data processor for both MFDs; and
- o Alphanumeric windows on the HUD and MFDs would display certain flight parameters, flight control mode advisory, system status, and failure advisories.

2.7.4 CONTROLLERS ANALYSES - Analyses and design have been conducted to define primary controller configurations and the control system mode selection, annunciation, and fault warning panel configurations. The analyses and design included controllers for:

- o Pitch, roll, and yaw,
- o Direct-lift and direct-side force,
- o Thrust,
- o Simultaneous selection of flight control mode and pertinent displays,

- Preflight operations,
- Data entry and displays, and
- Reset or correction.

The Digital FCS primary controller configuration includes a Side Stick Controller (SSC) for pitch and roll control, rudder pedals for yaw control, a controller for direct-lift and direct-side force controls and throttles for thrust control. Control system mode selection is accomplished through keys on the CDC, or by controllers located on the stick grip and throttle grip.

The controller locations and configuration evolved from consideration of:

- The FDL-MCAIR SFCS flight test program results,
- The FDL-MCAIR High Acceleration Cockpits Study results,
- The FDL-Boeing IIPACS study results,
- The results of this program's Pilot Interface Analyses,
- Conceptual engineering models, and
- Full scale design aids representative of the Digital FCS design.

2.7.4.1 Side Stick Controller - Pilot control of pitch and roll is provided by a side stick controller located on the right side of the pilot's seat in line with the pilot's normal arm position at his side. Figure 29 illustrates the digital FCS grip configuration used for the Control Law Simulation. A multifunction switch operates refuel disengage, IR weapon uncage and nose gear steering. During control law simulations the evaluating pilots generally disliked the isometric switch used for DLC and DSF. They stated that the isometric switch provided no pilot cue to indicate that the operational limit of the system had been reached.

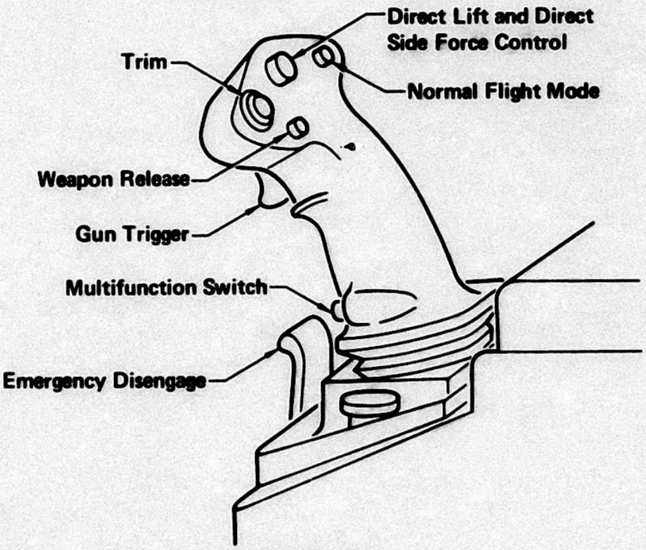


Figure 29
Digital FCS Grip Configuration

The SSC used during Control Law Simulation was the same one used in the SFCS and has its pivot point located at the base of the grip. This base-pivot SSC had an adjustable armrest and an adjustable neutral position. In addition, its installation provided for some fore and aft adjustment.

During the Control Law Simulation the pilots experienced sensitiveness in lateral control which they attributed primarily to the SSC. Consequently, the following changes were made to the SSC prior to the Integrated Control Law and Display Simulation:

- Up and down and rotational adjustment was added to the whole assembly,
- The armrest of the controller was made adjustable inboard and outboard with the front portion under the wrist adjustable up and down,
- The DLC and DSF isometric switch was altered to provide a small amount of displacement, and
- The position of the DLC and DSF switch was exchanged with the position of the trim switch.
- The weapon release button was deleted. (The weapon release button was moved to the throttle grip as shown in Figure 30 to alleviate the conflict of requirements for the thumb to operate simultaneously DLC, DSF and weapons release.)

Concurrently with the DFCS definition study, a palm-pivot SSC was in its initial stages of development at MCAIR. The palm-pivot SSC was designed so that the grip swivels about a point located approximately at its center. To control the airplane the pilot rotates the grip fore and aft about the point for pitch control and right and left about the point for roll control. At the conclusion of the Control Law Simulation, this controller became available for testing. Consequently, a parallel effort was initiated in which MCAIR pilots evaluated the palm-pivot SSC to determine its potential use during the Integrated Control Law and Display Simulation; the MCAIR pilots thought it would be better than the base-pivot SSC. Consequently the palm-pivot SSC, with improved adjustability, was used during the Integrated Control Law and Display Simulation.

During the Integrated Control Law and Display Simulation, the evaluation pilots found the palm-pivot SSC somewhat more comfortable, but still had difficulty tracking. On the last day of simulation, it was decided to try again the base-pivot SSC to see if tracking could be improved. All three customer pilots who evaluated the base-pivot SSC with the improved adjustability experienced improved air-to-air tracking. Statistical tracking data was not recorded, but it was visibly observed to be significantly improved with the base-pivot SSC. It is MCAIR's opinion that this improved tracking resulted primarily from the relocation of the SSC and through use of the additional adjustment provided for the SSC and its armrest. All three pilots during the final debriefing session stated their preference for the base-pivot SSC.

2.7.4.2 Rudder Pedals - Pilot control for yaw is provided by conventional rudder pedals. Full pedal travel was approximately 2.6 inches.

2.7.4.3 Throttles - Pilot control for engine thrust is provided by a throttle controller located on the left side of the pilot's seat in line with the pilot's normal arm position at his side. Figure 30 illustrates the Digital FCS throttle grip configuration used for evaluation during the Integrated Control Law and Display Simulation. The evaluation pilots' comments were, in general, that the switches and buttons on the throttles were well located except that the reach to the Air-to-Air Mode Select Button was too long.

The principal feature of the throttle controller was its relatively short travel which was less than one-half that of an F-4. Another feature is that all of its outputs are electrical. The throttle levers are also electrically driven to provide visual and tactile pilot cues, although this feature was not used during man-in-the-loop simulations. A clutch permits overriding the gear train with a force applied by the pilot. An adjustable armrest similar to the one on the SSC was provided. The evaluation pilots felt that the throttle location and adjustable armrest were satisfactory. They felt that the short throw throttle was good, but actual inflight tight tracking tasks, e.g., aerial refueling and formation flying, would be required for verification.

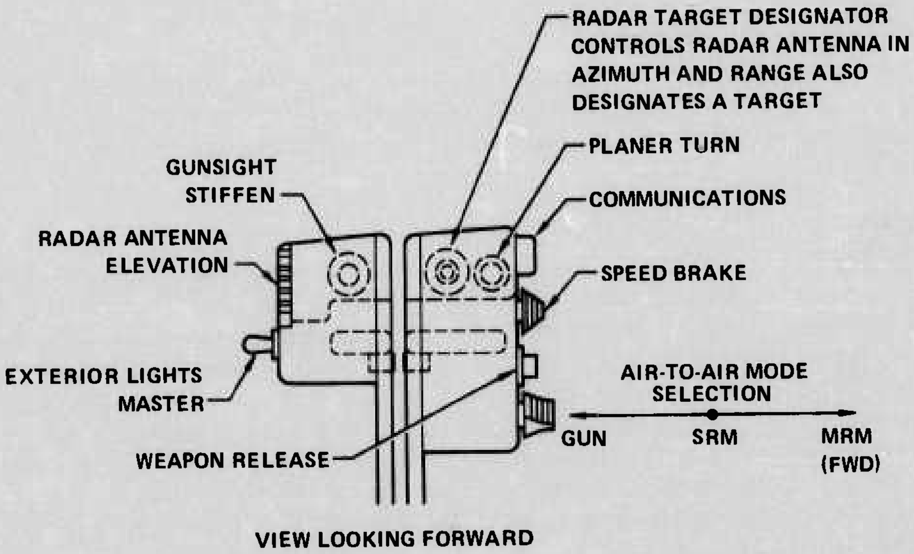


Figure 30
Throttle Grip Controllers

2.7.4.4 Controller Interrelationship - The controllers analyses included consideration of the interrelationship of the Digital FCS controllers with existing aircraft system controllers. Controllers for Digital FCS were identified by analyzing all pilot tasks required to complete the mission functions. The design aid included panels, displays, and controllers representative of a typical advanced single-place fighter aircraft. The pilot evaluations concluded that the overall relationships represented were satisfactory.

2.7.4.5 Computer and Display Controller (CDC) - The CDC is an input-output device which provides an interface between the pilot and the flight management computer. The lower portion contains an alphanumeric keyboard and several dedicated page select keys which provide for selection of flight control modes, display formats, navigation flight plans and checklists. The upper portion contains a CRT display to present pre-flight checklists, flight plans, flight progress, and other data.

The CDC used in simulation was originally designed by the Collins Radio Company as a control display unit for an area navigation system used in transport type aircraft. With some modifications, an excellent pilot-to-computer communication link was devised for use in a fighter aircraft with multimode control laws and mode-related advanced displays. Figure 31 is an illustration of the CDC. A more complete description of the CDC operation is contained in Reference (15). Following are some examples of CDC operation.

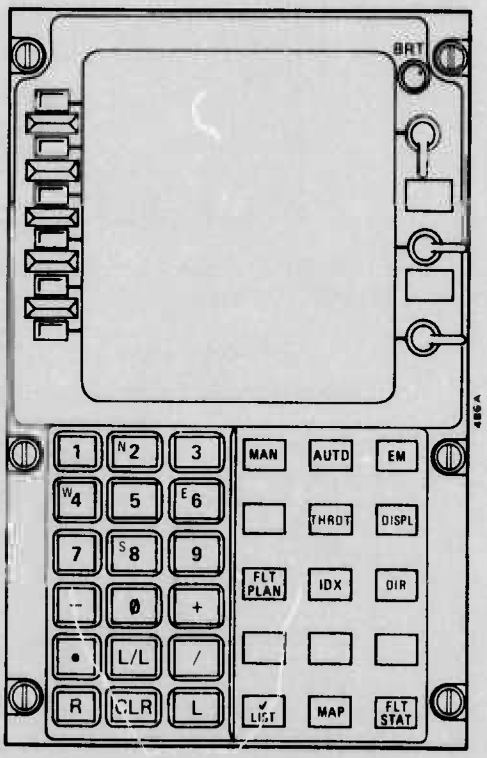
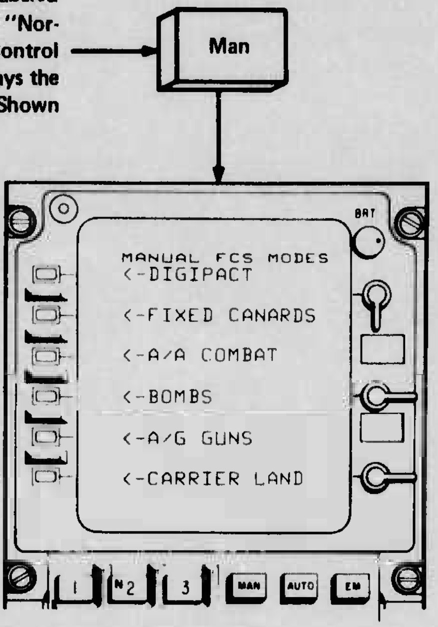


Figure 31
Computer and Display Controller

To select a control mode, the pilot pushes either the "MAN" page select key for a manual mode or the "AUTO" page select key for an automatic mode. Pushing the "MAN" key automatically engages the "NORMAL" flight control mode and displays the CDC page shown in Figure 32. Pushing the "AUTO" key automatically engages "ATTITUDE HOLD" and displays the CDC page shown in Figure 33. With either the manual or automatic mode CDC page shown, the mode desired is engaged by depressing a line select key adjacent to the listed mode. A caret depicted next to the listed mode and pointing toward the line select key means that the mode is available for selection without a prior action. To select the vertical navigation mode the Lateral Navigation Mode must be selected first, then the caret will appear adjacent to "NAV VERTICAL". To select the Automatic Heading Mode, the desired heading must first be inserted between the brackets, then the caret will flip over and point towards the line select key.

Pushing the Key Labeled "Man" Engages the "Normal" Flight Control Mode and Displays the CDC Page Shown

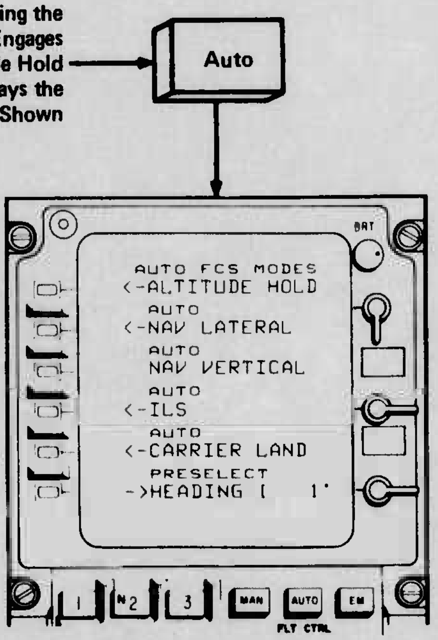


Selection of Any Line Key Engages the Mode Listed

"< –" Means the Adjacent Line Key is Available for Selection

Figure 32
FCS Manual Mode Selection on CDC

Pushing the "Auto" Key Engages Attitude Hold and Displays the Page Shown



Selection of Line Key Engages Mode Listed

"< –" Means the Adjacent Line Key is Available for Selection

Figure 33
FSC Auto Mode Selection on CDC

The simulation results indicated that a consistent means of selecting all flight control modes should be utilized, i.e., the "MAN" key should call up the list of selectable modes but not engage the Normal Mode.

Pushing the "FLT PLAN" key displays the flight plan page as shown in Figure 34. Listed on the page are all waypoints or checkpoints with the altitude at which the flight plan prescribes they be passed. The top listed waypoint is the next one to be passed. The course the pilot has selected to fly to the waypoint is noted above the waypoint name. To the right of the course notation is shown the pilot selected left or right offset from the original course. The flight plan can be slewed and waypoints can be added and/or deleted.

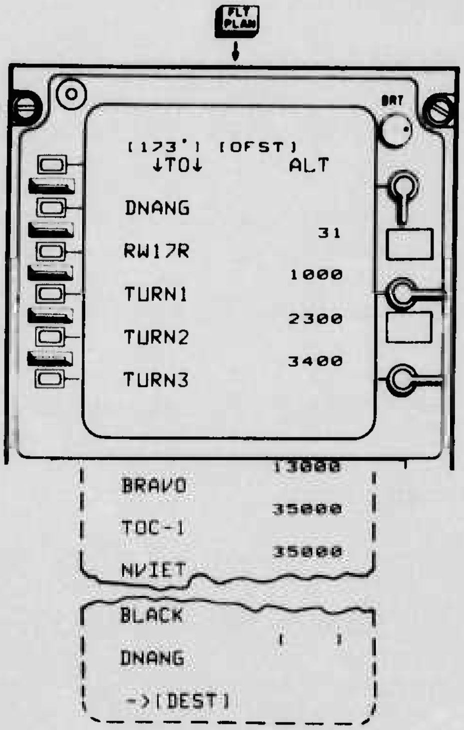


Figure 34
Flight Plan on CDC

Results of simulations showed that operation of the CDC was easy to learn. The pilot-computer interface concept demonstrated was readily accepted by evaluation pilots. Controller functions integrated into the CDC were limited by program-scope to those directly related to multimode flight control and pertinent displays. However, a number of other controller functions are attractive candidates for integration and time-sharing, e.g., Inertial Nav, Communication, IFF, Radar and EO Sensors. Potential benefits to be derived from integration and time-sharing of other controller functions are:

- More efficient use of panel space,
- Increased pilot efficiency, and
- Reduced cost of ownership.

2.7.4.6 Conclusions - As a result of the evaluation pilots comments made during the Integrated Control Law and Display Simulation the following conclusions have been made:

- In general, the location of the SSC and throttles in the cockpit was satisfactory;
- The Air-to-Air Mode and Normal Mode selection through controllers located on the throttles and SSC, respectively, was well liked because it permitted hands-on-controller operation during periods of high activity or stress;
- The Direct-Lift and Direct-Side-Force controller should provide a small amount of displacement;
- The base-pivot SSC was easier to learn and permitted more effective tracking;
- The SSC mechanization, e.g., grip shape, travels and breakout forces, needs improvement;
- The switches and buttons on the throttle are well located, except that the reach to the Air-to-Air Mode select button was too long; and
- The short-throw throttle was satisfactory in simulation, but needs to be evaluated in flight.

To accommodate different size pilots all side-mounted controllers need provisions for:

- Up and down adjustment with the seat,
- Rotational adjustment,
- Inboard and outboard adjustment of the armrest, and
- Up and down adjustment of the armrest under the wrist.

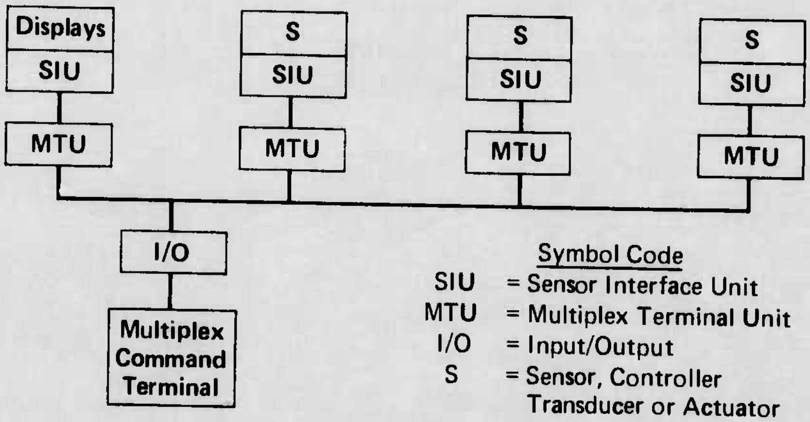
The CDC was considered outstanding. The simulation results indicate that:

- The simultaneous selection of a flight control mode and its related display through the CDC was "super";
- The CDC operation and switchology was easy to learn;
- The CDC data update rate should be increased;
- Selection of the Normal and Attitude Hold Modes via the CDC should be accomplished using the CDC line select key rather than being engaged simultaneously with the selection of the page "MAN" or "AUTO"; and
- Completed portions of the flight plan should remain available for recall by the pilot.

2.8 MULTIPLEX ANALYSIS

The application of digital computers to the flight control system suggests that multiplexing and digital signaling between the digital computers, sensors and actuators might offer significant advantages. Accordingly, the application of multiplexing to DFCS was investigated and the analysis is summarized below.

2.8.1 TRANSMISSION NETWORK - The first basic decision relative to the structure of the multiplex network candidates was that multiplexed signaling, if used, should be channelized, i.e., should have the same degree of redundancy as the computers. This decision is dictated by safety and reliability considerations and does not make maximum use of multiplexing, since it would clearly be possible to transmit data from redundant sensors over a single multiplex transmission line to each of the redundant digital computers. Having decided on a channelized multiplexing arrangement, three candidate networks were analyzed. The networks represent a typical Digital FCS Channel and are presented in Figures 35, 36, and 37.



Symbol Code

SIU = Sensor Interface Unit
MTU = Multiplex Terminal Unit
I/O = Input/Output
S = Sensor, Controller Transducer or Actuator

Advantages

- **Growth Capability**
- **Parts Commonality**
- **High Data Capacity**
- **Short Circuit Isolation**

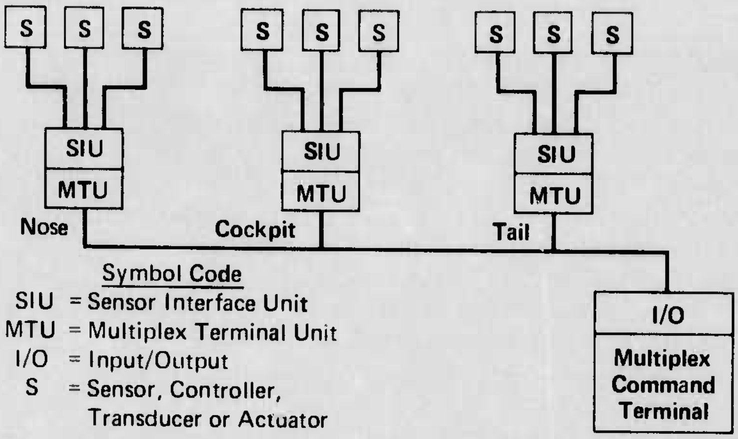
Disadvantages

- **High Relative Complexity**
- **High Relative Cost**

Figure 35
Party Line Multiplex Network

Figure 35, Party Line Multiplex Network, has all of the advantages which have justified its use in current aircraft electronic multiplex systems. However, the growth capability of the party line network may not be realized since the probability of adding sensors, transducers or actuators to the inner loop of a flight control system is low. The added complexity and cost of this type of multiplex network does not appear to be warranted.

Figure 36, Area Multiplex, represents a middle ground with respect to flexibility and cost. The analysis did not indicate that the advantages warranted installation of area multiplex terminals.

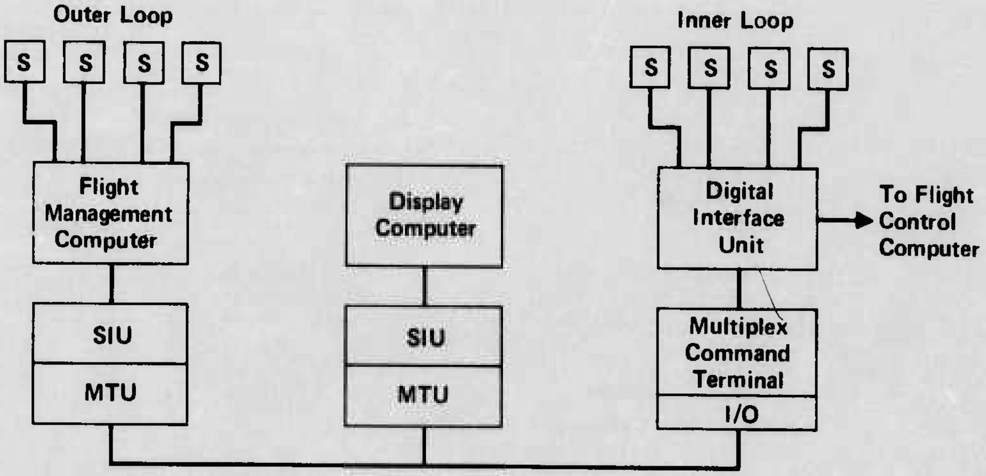


Symbol Code

SIU = Sensor Interface Unit
MTU = Multiplex Terminal Unit
I/O = Input/Output
S = Sensor, Controller, Transducer or Actuator

Advantages	Disadvantages
• Moderate Complexity	• Not Easily Expanded
• Moderate Cost	• Limited Growth
• Moderate Data Capacity	

Figure 36
Area Multiplex



Symbol Code

SIU = Sensor Interface Unit
MTU= Multiplex Terminal Unit
I/O = Input/Output
S = Sensor, Controller, Transducer or Actuator

Advantages	Disadvantages
• Low Relative Cost and Complexity	• Common-Mode Sampling
• Time Shared A/D Conversion	• Limited Data Capacity
• Simplified Digital Signaling	• Short Circuit Susceptibility
• Simplified Time-Slot Address	

Figure 37
Central Digital Interface with Display and Flight Management Computer Multiplex

Figure 37, Central Digital Interface with Display and Flight Management Computer Multiplex, represents a network which uses dedicated wiring for the redundant sensors, transducers, and actuators, but utilizes multiplexing for the non-redundant display and other simplex outer loop sensors which are utilized by the Digital FCS. This scheme makes the redundant flight control system compatible with use of a party line multiplex network which is connected to the display and flight management computers, which in turn are connected to the outer loop sensors of the aircraft. Multiplexing in this area may offer advantages because it is likely that the outer loop sensors in advanced aircraft will be connected by a multiplex network and it is also more likely that any growth of the flight control system after initial installation will occur in the area involving simplex outer loop equipment. For example, additional automatic modes might be added to the flight control system by providing additional inputs to the Digital FCS over the abovementioned multiplex transmission line.

2.8.2 TRANSMISSION METHODS - Analysis indicates that the transmission method which is most appropriate for the Digital FCS is a transformer-coupled, balanced transmission line to provide a high degree of noise rejection. The balanced line also permits use of a twisted-shielded-pair to minimize mutual coupling of noise fields. Biphase-level (Manchester II) baseband signaling is used to provide low bit-error-rate and self clocking operation.

2.8.3 DATA BUS OPERATION - The data bus operation recommended for the Digital FCS is a command-response type control to transfer sensor data to a central digital processor in response to software initiated commands. Consequently, data is constantly available for processing at the current sequence in the computational cycle. Asynchronous decoding uses the inherent signal transition in each bit of biphase data to establish timing.

Since timing in the asynchronous receiver is derived directly from the data bit stream, there is no need for external sources of timing. In contrast, the propagation delay between clock and data in synchronous operation imposes a practical limit on transmission line length.

2.8.4 MULTIPLEX TERMINAL - The recommended multiplex terminal arrangement is an asynchronous biphase integrating receiver. The integration technique is used to measure time between axis crossings; consequently, a significant pulse-to-pulse jitter can be tolerated without causing errors in the detection process. As a result, the integrating receiver has a lower bit-error-rate for a given signal to noise level than pulse-gated, one-shot receivers.

2.8.5 CONCLUSIONS - The analysis indicated that multiplexing of the redundant, analog inner loop sensors, transducers and actuators was not justified because of the relative simplicity of the wiring and low probability of changes after initial system verification.

Multiplexing between the digital interface unit, and the display and flight mangement computers appears to be appropriate and advantageous. The transmission methods, data bus operation and terminal configurations were determined. The multiplexing techniques recommended are compatible with MIL-STD-1553.

2.9 LIGHTNING PROTECTION

The lightning protection scheme and analysis for the Digital FCS aircraft is summarized in the following paragraphs.

2.9.1 THREAT DEFINITION - A lightning strike threat for the Digital FCS aircraft was defined. The lightning strike model is presented in Table 5 and Figure 38. A comparison between the Digital FCS lightning strike model and the lightning model of MIL-B-5087 is presented in Table 6.

Table 5
Digital FCS Lightning Strike Model

Return Strokes					Intermediate Current Model		Continuing Current	
Stroke Order	Peak Current (kA)	Charge (C)	Time Between Strokes (ms)	Model Current, I_o (kA)	I_i (kA)	Charge (C)	I_c (A)	Charge (C)
1	200(4)	~12		206	9	~8		
			60					
2	100	~6		103	9	~8		
			60					
3	100	~6		103	0	0	Final Stage (3)	
							400	~160
Total Charge Transformed		~24(1)				~16(1)		~160(1)

(1)= Total Charge Transferred ≅ 200C, Total Strike Duration = 0.5 sec

(2)= The time history for all strokes is defined by $I(t) = I_o (e^{-\alpha} - e^{-\beta t}) + I_i (e^{-\gamma t} - e^{-\delta t})$ with $\alpha = 1.7 \times 10^4 \text{ s}^{-1}$ $\beta = 3.5 \times 10^{6o} \text{ s}^{-1}$ $\gamma = 10^3 \text{ s}^{-1}$ $\delta = 10^4 \text{ s}^{-1}$. The time to peak current is 1.5 μs for all strokes. The time to half-value is 40 μs for all strokes.

(3)= Final stage continuing current (I_c) duration = 400 ms

(4)= Action integral = 1.9×10^6 ampere^2 - seconds

The rationale for utilizing this model is summarized as follows:

- It is representative of the highest currents to be expected (98% of the strike data surveyed is lower).
- The rise time is representative of the fastest rate of rise expected and is still practical for simulation (98% of probable strikes will be slower).
- The number of strokes per strike, interval, half amplitude decay time and coulomb transfer represent mean values. This is considered appropriate since a high performance aircraft, even at landing speed, will have traveled through an established strike channel in less than one half second.
- The model assumes a subsystem is sensitive to high peak currents, high total charge transfer, high di/dt, high charge transfer in a single stroke, and insensitive to stroke interval. In the latter case, in the event that subsystem information rates are considered a factor, the interval may be varied to evaluate vulnerability.

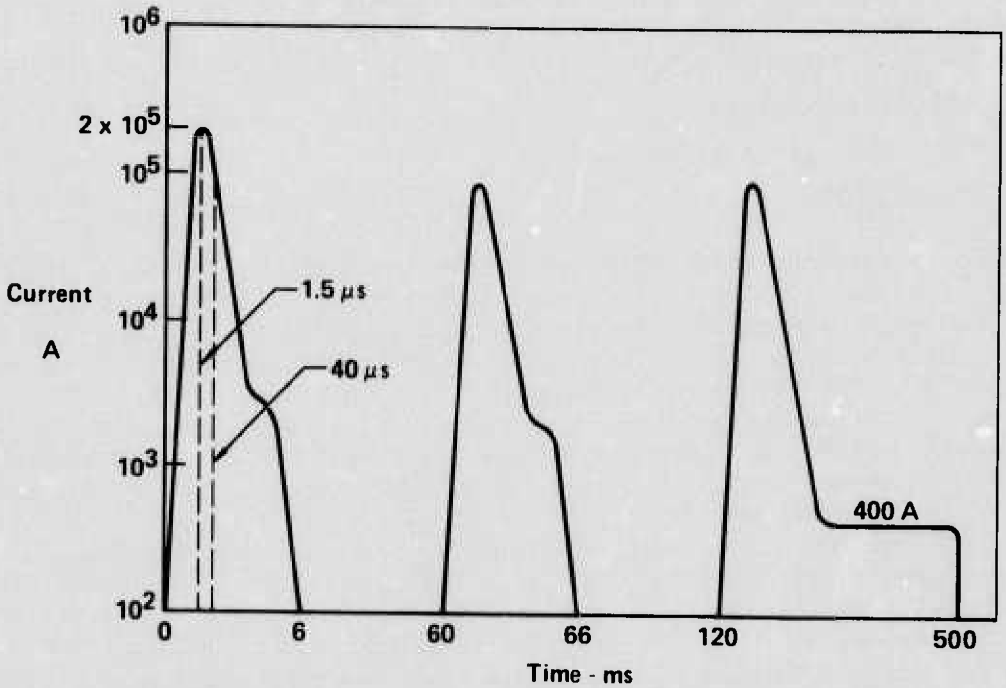


Figure 38
Digital FCS Lightning Strike Model

Table 6
Lightning Strike Model Comparison

	MIL-B-5087	Digital FCS Study*
Lightning Strokes/Strike	1	3
Peak Current (kA)	200	200
Rate of Rise (kA/μs)	100	133
Follow on Current	None	400 A for 380 ms
Total Coulomb Transfer	5.5	200
Mean Decay Time to 1/2 Value (μs)	20	40
Intermediate Current Level (kA)	None	9
Estimated Percent of Lightning Strikes Covered	10%	50% (Mean)

*Based on Severe Applied Lightning Model per Stanford Research Institute Contract Report L.S. -2817-A 3 August 1972

kA – 1000 amperes
ms – millisecond
μs – microsecond

2.9.2 ATTACH ZONES - Lightning strike attachment on any aircraft can be divided into zones. There are four basic aircraft lightning zones. These are:

- Direct attachment zones,
- Swept stroke zones,
- Current transfer zones, and
- Clear zones.

Direct attachment zones of interest are those where lightning initially attaches or exits. These are the nose, canard tips, wing tips, wing pylons and stores, and empennage extremities (rudder and stabilator tips). It can be shown that on a high performance jet aircraft, configuration dependent electrostatic criteria will limit the direct attachment points to those mentioned with very few exceptions. A swept stroke zone is an area in which a lightning stroke is swept back from the initial attach point by the airstream. This is the direct result of the aircraft flying through or away from an established lightning channel. The swept stroke zones are easily defined as the locations behind direct attach zones such as fuselage and possibly the wing torque box. The current transfer zone is an area through which lightning current passes, but which is outside of the direct attachment or swept stroke zones. These areas must transfer the lightning current between the attach and exit points. The remaining area is a clear zone. These are areas where lightning does not attach and associated current does not pass through. For the lightning vulnerability study, the only zone of interest is the current transfer zone.

2.9.3 VULNERABILITY EVALUATION - The lightning strike threat described above was applied analytically to the Digital FCS. Quantitative values of voltage and time duration of electrical transients resulting from the assumed lightning strike model were calculated and are summarized in Table 7.

The vulnerability analysis thus identified potentially vulnerable wires and circuits and the magnitude of the potential lightning transients.

2.9.4 PROTECTIVE MEASURES DEFINITION - Having determined the potentially vulnerable wires and circuits of the Digital FCS, protective measures were devised in an attempt to cope with the potentially disruptive effects of the assumed lightning strike.

It is planned that the results of this analysis will be used to provide specification requirements relative to lightning protection measures for Digital FCS equipment and provide guidelines for aircraft design so that appropriate lightning protection will be provided in the Digital FCS test aircraft.

2.9.5 TEST CRITERIA AND FACILITIES - A summary of lightning test criteria and facilities appropriate to verify the lightning protection provisions of the Digital FCS aircraft was prepared. The analysis indicated that full scale (high current and high voltage) lightning tests on the complete aircraft would provide the most credible data relative to vulnerability to lightning. However, it is recognized that full scale lightning tests involve potential risk to the aircraft and/or the installed equipment being evaluated. It was further concluded that nondestructive,

Table 7
Lightning Vulnerability Analysis Summary

Circuit Identification	Induced Voltage/Current	Duration	Function Affected	Circuit Damage Potential
Multiplex Transmission Line (Forward Area) (Full Fuselage)	15.6V 26V	≅ 1 μs ≅ 1 μs	Yes Yes	Marginal Marginal
Secondary Actuator Servo Valve	6 μa	≅ 150 μs	No	Marginal
Secondary Actuator Position Feedback	2.5V Secondary 0.3V	≅ 1 μs, 4.25 kHz 1 Cyc	No	No
Secondary Actuator ΔP Demodulator	30.5V Secondary 5V	≅ 1 μs ≅ 40 μs	No	Marginal No
Input to Secondary Actuator Shut-Off Valve and ΔP and Position Primaries	61V	≅ 1 μs	No	No
Side Stick Command Demodulator	18V Secondary 5V	≅ 1 μs 8.8 kHz 1 Cyc	No	Marginal
Rate Gyro Demodulator	36V	≅ 1 μs	No	Marginal
Accelerometer	36V	≅ 1 μs	No	Marginal
Rudder Pedal Transducer	36V	≅ 1 μs	No	Marginal
DC Power	5.7Vx10^5 Secondary 3.0Vx10^3 (Opposite Polarity)	≅ 1 μs ≅ 160 μs	Yes	Yes

Marginal: Voltage or current is below damage or upset level but within the safety margin of 10 to 1

transient analysis type lightning testing would provide data which could be extrapolated to estimate the potential effects of full scale lightning strikes. It is planned that transient analysis tests will be conducted on the test aircraft.

2.9.6 <u>COMPOSITE STRUCTURE CONSIDERATIONS</u> - Composite materials, which possess superior structural properties when compared to conventional metallic materials, are being developed for use in future tactical aircraft. The composite materials currently being developed and evaluated are vulnerable to lightning strike damage, and may provide little or no lightning protection for wiring or equipment installed behind them.

The most common composite materials being considered at this time are boron epoxy and graphite epoxy. When compared to metal, these composite materials are poor conductors of electrical current. This relatively poor conductivity is the reason for their vulnerability to lightning.

The effect of lightning on a tactical aircraft, utilizing composite structural parts and fly-by-wire flight control, is basically two-fold. First, lightning may cause structural failure of the composite structure and this effect presents a hazard to the flight integrity of the aircraft. Secondly, lightning may penetrate a composite structural part of the aircraft and enter directly or induce an effect in the fly-by-wire flight control system.

Investigation of composite protection methods reveals seven basic approaches which are:

- Thin metal strips over the composite area separated by a dielectric coating,
- Overall metal coating of the composite area,
- Metal mesh overlays,
- Bus bars,
- Graduated impedance ionization strips,
- Diversion (around or away), and
- Dielectric coatings.

When replacing portions of an airframe with composites, specific approaches will be required to provide solutions for the specific problem areas. The protection approach considered for any particular composite area or structure is dependent upon the zone of interest.

One point, which becomes apparent, is that all of the suggested lightning protection techniques end up adding weight to the aircraft. The weight of lightning protection provisions should be added to the weight of the composite in determining overall weight advantage of the composite over conventional metal construction.

Once the approach is established the primary objective is still to keep lightning currents out of composites and direct the current to metallic structure for diversion and control. In addition, the current transfer paths across composite structures from the attach points to the airframe must be designed with as few bends or twists as possible to reduce the resultant inductance to a minimum.

2.9.7 CONCLUSIONS - A lightning strike threat model was selected. The model was used to analytically evaluate vulnerability of representative DFCS circuits. Protective measures, aimed at reducing vulnerability of circuits identified as potentially susceptible were summarized. Considerations relative to lightning testing and composite structure considerations were evaluated. The approach used in the lightning protection analysis proved to be satisfactory, and appears to provide a coherent approach for defining lightning protection design and test criteria for a digital or analog fly-by-wire system in any fighter type aircraft.

2.10 ELECTROMAGNETIC COMPATIBILITY (EMC)

An EMC analysis of equipment of the types needed to implement the DFCS was conducted. The EMC analysis considered equipment and wiring to implement both analog and digital signal transmission. Particular attention was directed toward equipment which was different from that used to implement the SFCS, e.g., digital computers and electronic displays.

A conventional scheme for implementation of EMC of the DFCS has been identified and is summarized below.

2.10.1 EMC BONDING TECHNIQUES - Electrical bonding is recommended for application to the DFCS and aircraft per MIL-B-5087B as provided by MCAIR Process Specifications. Electrical bonding consists of direct metal-to-metal contact of DFCS related components (units-to-structure, shields-to-chassis) to provide a low impedance path. This will help ensure that the DFCS system and subsystems are electrically stable and free from static discharge and electrical shock hazards. In addition, bonding establishes the equipotential base for DFCS radio frequency (RF) emission control and suppression.

2.10.2 EMI GENERATION AND SUSCEPTIBILITY CONTROL - It is recommended that control of DFCS equipment EMI generation and susceptibility be accomplished through the application of appropriate portions of MIL-STD-461, Notice 3 and MIL-STD-462, Notice 2 (subsystem electromagnetic interference control design and test requirements respectively) on all DFCS and related equipment. For those subsystem units which have been previously developed to earlier specifications, parts of MIL-STD-461, and 462 will be specified to establish the same EMC confidence as the newly developed equipment.

2.10.3 EMC GROUNDING PROVISIONS - It is recommended that the grounding technique for the DFCS adhere to the single point ground concept for all DFCS circuits including the DFCS power control, with the exception of RF shields. This concept requires that all subsystem interface circuits be grounded at one end only and be electrically isolated for both AC and DC at the other. It is planned that the single point ground concept will be specified to all subsystem manufacturers. The single point grounding of interface circuits will help to eliminate ground plane induced noise in the system.

2.10.4 EMC AIRCRAFT WIRING TECHNIQUES - Aircraft wiring guidelines will recommend that analog and digital flight control signal circuits be shielded. It is planned that noise generation and immunity in power and discrete logic wires will be controlled by filtering and that the shields of DFCS analog circuits will be grounded at the signal source end (or interface ground point) for maximum effectiveness. It is also planned that digital circuits will have RF shields grounded at both ends and at all breaks. RF shields are recommended because digital signals have high frequency components due to the fast rise and fall times of the information transfer.

Wire or cable separation is another aircraft wiring technique available for EMI control. Of particular concern in aircraft wire-to-wire coupling analysis are the aircraft primary power and RF transmission lines. To reduce the probability of these lines affecting the DFCS, their routing will be maintained at least six inches from DFCS wiring and/or cabling where feasible.

2.10.5 SUBSYSTEM INTERFACE CONTROL - Without interface control, other EMC design considerations are either partially or totally ineffective. Interface control involves establishing system input or output circuit configurations with EMC as an objective. One of the better circuit configurations for common mode noise rejection and utilization of other EMC techniques is a balanced pair (source and return) with respect to ground. It is therefore planned that all DFCS digital lines will utilize this type of interface.

2.10.6 CONTROL OF DEGRADING EFFECTS OF AIRCRAFT ENVIRONMENT - Control of degrading effects of the aircraft environment on the DFCS requires maintenance of the fuselage as a continuous, low impedance, enclosed structure thereby providing an equipotential ground plane for RF shielding. It is planned that structural discontinuities such as hinged doors and inspection cover plates will be examined to ensure that proper bonding is maintained. Any non-conductive skin section additions will be analyzed to determine if aircraft and DFCS wiring or equipment should be relocated.

2.10.7 CONCLUSIONS - The EMC techniques summarized above provide comprehensive coverage against EMI relative to the DFCS installation. Total system testing will generally follow MIL-E-6051D. Implementation of EMC based on the scheme summarized above has proved to be adequate on current and past programs at MCAIR. There is always some potential for problems resulting from inadequate EMC on an ADP such as DFCS. However, it is anticipated that with proper attention to the schemes and guidelines summarized above, satisfactory EMC will be achieved.

2.11 BUILT-IN TEST AND INFLIGHT INTEGRITY MANAGEMENT (BIT AND IFIM)

2.11.1 GENERAL - As used in this report, BIT is a sequence of tests conducted on the ground to validate and/or troubleshoot the system. IFIM is a sequence of tests conducted while the system is operating, to monitor performance. The BIT and IFIM studies were conducted in conjunction with the Redundancy Management and/or IFIM Analyses. The areas of investigation for these studies were complementary. The redundancy management and/or IFIM analyses summary, Section 2.12, addresses the areas of common interest and specifically covers the IFIM. The functions of pilot preflight, maintenance preflight, and maintenance troubleshooting are combined into a single test program with subroutines for expanded tests as discussed in the following paragraphs.

2.11.2 BUILT-IN TEST - The Built-In Test (BIT) is planned to be designed to permit rapid and positive organizational level maintenance of the DFCS, without the need for special test equipment or highly skilled technical personnel. Fault detection to a module level is not planned. Detected LRU faults will be reported and identified. Electronics can be tested and fault isolated with or without application of hydraulic power. This provides for a reduction in actuator wear, minimizes manhours to repair, minimizes AGE or GSE requirements, facilitates deck handling, and increases aircraft availability.

BIT will be inhibited by series interlocks. A BIT initiate switch must be energized external to the cockpit by a ground crewman before the cockpit BIT initiate switch can be energized. This is to permit visual checks from ground level to assure that all surfaces are clear and safe to operate. Additional provisions will be implemented to preclude inadvertent activation of the BIT program in flight.

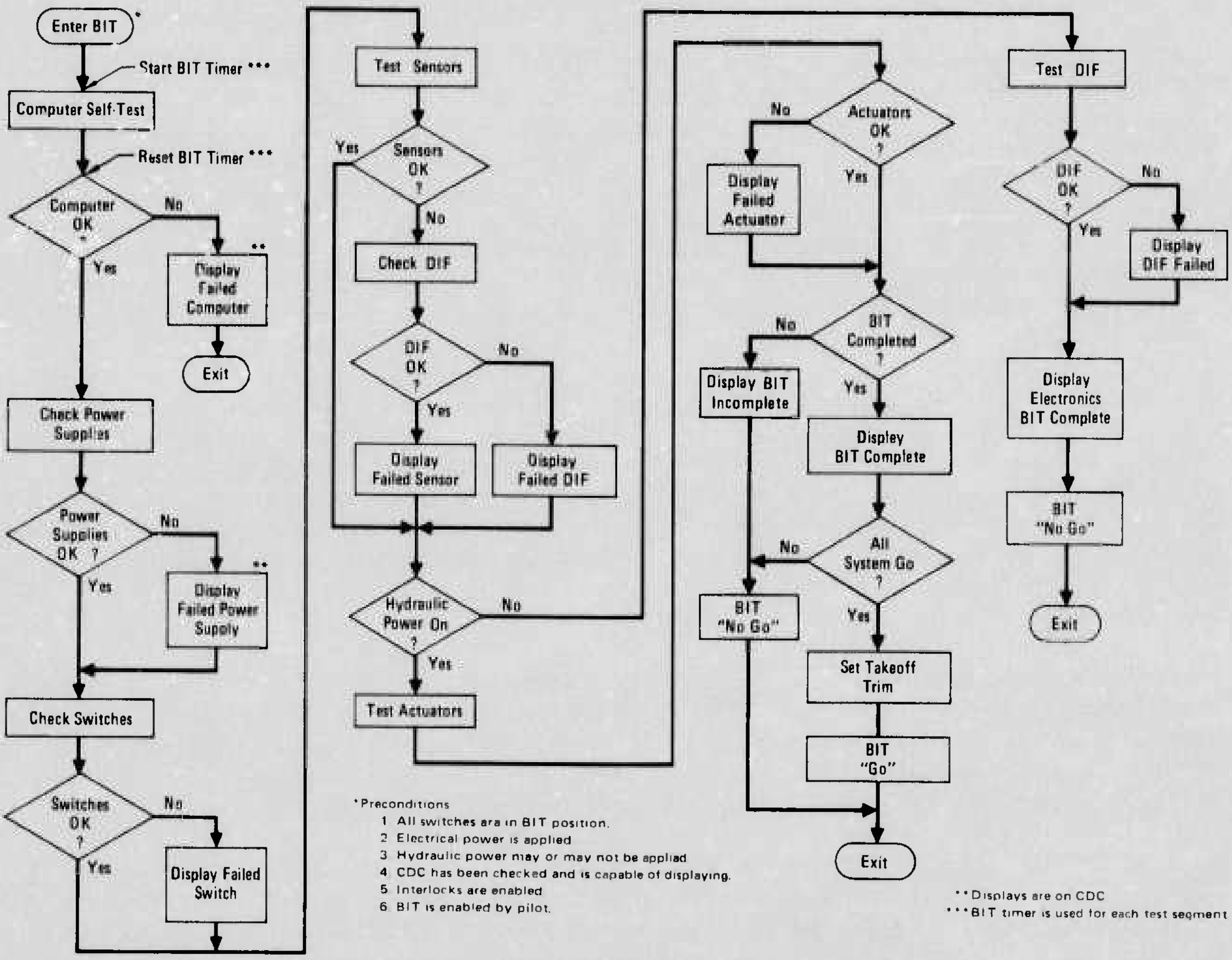
BIT verification will be by analysis and by test. It is planned that the BIT verification test will evaluate functional failures based upon a failure modes and effects analysis and a hazard analysis which identify all failures. Flight safety and mission critical failures, and a random selection of faults will be induced in the equipment to verify that the monitoring schemes are capable of detecting and isolating faults to the desired levels.

The time to perform BIT, excluding time for test preparation, is estimated to be as follows:

BIT (with hydraulics)	≅ 20 seconds (triplex) ≅ 29 seconds (quadruplex)
BIT (without hydraulics)	≅ 10 seconds

The BIT scheme is planned to be a software controlled test. Maximum use will be made of IFIM monitors to detect and isolate faults. Dynamic stimuli will be inserted at discrete intervals during the test in order to exercise those elements of the system that are not amenable to static test. Sensors, controllers and actuators will be exercised and the resulting outputs compared, voted, and in-line monitored to check proper operation. The computers will be self-tested, cross-channel monitored and voted. Fault isolation subroutines will be automatically initiated when a test failure result is ambiguous. Failure threshold settings for BIT may be tighter than IFIM in order to detect marginal conditions or incipient failures.

The overall BIT scheme flow diagram is illustrated in Figure 39.



*Preconditions

1. All switches ara in BIT position.
2. Electrical power is applied
3. Hydraulic power may or may not be appliad
4. CDC has been checked and is capable of displaying.
5. Interlocks are enabled
6. BIT is enabled by pilot.

**Displays are on CDC

***BIT timer is used for each test segment

Figure 39

Top Level Flow Diagram Depicting Preflight BIT

2.11.3 INFLIGHT INTEGRITY MANAGEMENT (IFIM) - IFIM will be implemented using in-line monitoring, cross-channel monitoring and data reasonableness as discussed in Section 2.12.

2.11.4 DEDICATED HARDWARE VS SOFTWARE FOR BIT AND IFIM

Analyses were conducted to evaluate the advantages of using hardware vs software to implement the various schemes for BIT and IFIM. The analyses are summarized as follows:

- Signal conditioning requirements were identified which could only be accomplished by hardware. These functions are not candidates for implementation in software.

- Monitoring tasks which can be accomplished by hardware or software, can be accomplished equally well by hardware or software. Performance was therefore not a trade-off issue.

- Implementation of monitoring tasks in hardware rather than software always results in a higher channel failure rate (because of the failure rate of the added parts) and consequently results in a higher probability of loss of control.

- Monitoring of analog signals can be more easily accomplished by a hardware monitor (no analog to digital conversion is required). However, no requirement for monitoring a signal where both the input and output were in analog form were identified.

- There is no known way to accomplish the actuator monitoring scheme presented in Section 2.12.7 using hardware.

- Examples of monitors which are planned to be implemented in hardware include:

  - Power supply monitors, and

  - Dead man timers.

2.11.5 CONCLUSIONS

- BIT should be a manually initiated, software controlled test.

- IFIM monitors should be used to detect faults.

- BIT should be carefully designed to assure that BIT operation in-flight is inhibited.

- A BIT Verification Test should be performed as part of the Flight Worthiness Test to validate the BIT design.

- Whenever there is a choice between hardware and software for implementation of a BIT or IFIM monitor, a software monitor should be used.

2.12 REDUNDANCY MANAGEMENT AND/OR IFIM ANALYSIS

2.12.1 GENERAL - Redundancy management and IFIM are defined as follows:

In Order to Assure Safe Aircraft Operation and Achieve a Required High Probability of Mission Success, Redundant Flight Control Units (Computers, Sensors, Actuators, etc) and Redundant Channels are Required.

The Process by Which:

- System Units are Monitored,
- Faulty Units are Detected and Isolated from the System, and
- The Remaining Good Units are Reconfigured

Is Defined as

Redundancy Management

Functional Implementation of this Process Includes:

- Cross-Channel Monitoring, and
- In-Line Monitoring, and

Is Defined as

In-Flight Integrity Management (IFIM)

When Implemented Properly, the FBW System will be

Fault Tolerant

Figure 40 shows that faults are detected by cross-channel and in-line monitoring and that recovery from faults is achieved by system reconfiguration. Some important considerations in implementing cross-channel monitoring are shown in Figure 41. Similarly, some important considerations involved in in-line monitoring are shown in Figure 42. Some techniques that can be used to reconfigure the Digital FCS to isolate and recover from faults are given in Figure 43.

Six initial candidate configurations were selected for analysis by MCAIR and three subcontractors (GE, Honeywell and Lear Siegler). The initial candidates ranged in complexity from simplex to quadruplex and other arrangements with degrees of redundancy between the two extremes.

After preliminary analysis of the initial candidates, three sound candidates were selected for detailed investigations of safety, mission performance, flexibility, pilot factors, reliability, survivability, maintenance and relative cost. Figure 44 illustrates the approach to Configuration Development and lists the initial and sound candidate configurations.

Faults are Detected by:

- Cross-Channel Monitoring
  - Yields High Coverage (→ 100%) of First Fault
  - Minimum Disruption of Normal System Operation
- In-Line Monitoring
  - Provides Fail Operational Capability with Two Channels

Faults are Isolated and Recovery from Faults is Achieved by:

- System Reconfiguration

Figure 40
Fault Detection and Isolation

- Number of Voting Planes
  - Sensor and Controller Inputs to Computer
  - Intermediate Computed Parameter
  - Computer Outputs to Actuators
- Computer Monitoring of Actuators
  - ΔP Comparison
- Redundant Data Comparison and Voting
  - Signal Selection
  - Averaging
- Computer Synchronization
  - Bit by Bit
  - Frame
  - Comparison of Intermediate Computational Results
  - Asynchronous
- Computer Interchange of Redundant Data

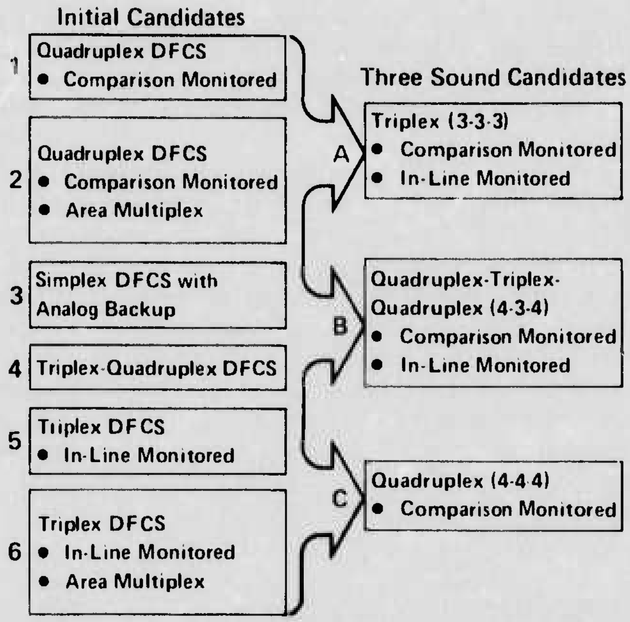
Figure 41
Important Considerations in Cross-Channel Monitoring

- Computer Self-Test
- Computer Test of Sensors and Controllers
  - Data Reasonableness
  - Torquers
  - Dither
- Computer Test of Actuators
  - Actuator Models
- Computer Test of I/O and Multiplex
  - Parity
  - Wraparound
  - Rebound
- Computer and Hardware Test of Power Supplies
- Data Reasonableness

Figure 42
In-Line Monitoring Considerations

- Isolate Failed Element
- Code Input Data from Failed Element to Identify it as Invalid
- Computer and I/O Restoration
  Two Examples:
  - Transient Failure Temporarily Affects a Computation
    Solution: Program Rollback
  - Data in Memory is Permanently Altered
    Solution: Reload Memory from Good Computer
- Alter Modes
  - Substitute Prime Data Source with Computed Data
  - Change Gains to Compensate for Faults
  - Alter Priority of Computations

Figure 43
System Reconfiguration Techniques



Note:
Numbers following configuration name indicate levels of redundancy for sensors, computers, and actuators respectively

Figure 44
Configuration Development

2.12.2 <u>REDUNDANCY MANAGEMENT REQUIREMENTS AND ISSUES</u> - Analyses were conducted to establish a redundancy and fault tolerant scheme for the candidate DFCS configurations. The analyses have considered the issues that are summarized in the following paragraphs.

2.12.2.1 Coverage

Objective

The objective of this study was to show the effect of coverage on the probability of loss of control function. Coverage is the probability of detecting, isolating, and recovering from a fault or failure.

Conclusions

- The first fault coverage for a triplex system and the first and second fault coverage for a quadruplex system must be high (greater than 0.99985) as shown in Figure 45.
- High first-fault coverage (essentially 1.0) can be achieved using force-summed secondary actuators because the minimum coverage is equal to the reliability of the isolation device (3×10^{-14} failures per operating hour).
- The equation for second fault coverage in a triplex system is given in Figure 46. For the set of representative coverage and failure rate numbers shown, the second fault coverage is 0.944.

- Given a first fault coverage of one and the set of failure rates and coverages of Figure 46, the failure probability of a triplex system is less than that allowed by the SOW (one failure per 1.5 million operating hours)[1]. This is shown in Figure 47. This demonstrates the feasibility of a triplex DFCS using in-line monitoring of second fault failures.

- A group of generic quadruplex and triplex systems are compared in Figure 48. Quadruplex system Q-1 has a third fault coverage of 0.95. To achieve this level of coverage requires the same in-line monitoring techniques used in the triplex system. System Q-2, on the other hand, requires only a simple "heads-or-tails" test for third fault coverage. Since its probability of loss of control is much better than required (one failure per 1.5 million operating hours), it would appear to be the preferred quadruplex system. Triplex system T-1 has a second fault coverage of 0.95 which is conservative and readily achievable with known in-line monitoring techniques. It is theoretically possible to achieve a second-fault coverage of 0.99 and the probability of loss of control shown by T-2. For any triplex system to have as low a probability of loss of control as quadruplex system Q-2 requires a second fault coverage of 0.9996 (system T-3) which is extremely unlikely.

NOTE 1: The Statement of Work reliability goal is no more than two failures per 10^6 flight hours. For purposes of the analysis it was assumed that the ratio of operating hours to flight hours was three. The SOW therefore requires no more than 2 failures in 3 x 10^6 operating hours or no more than 1 failure in 1.5 x 10^6 operating hours.

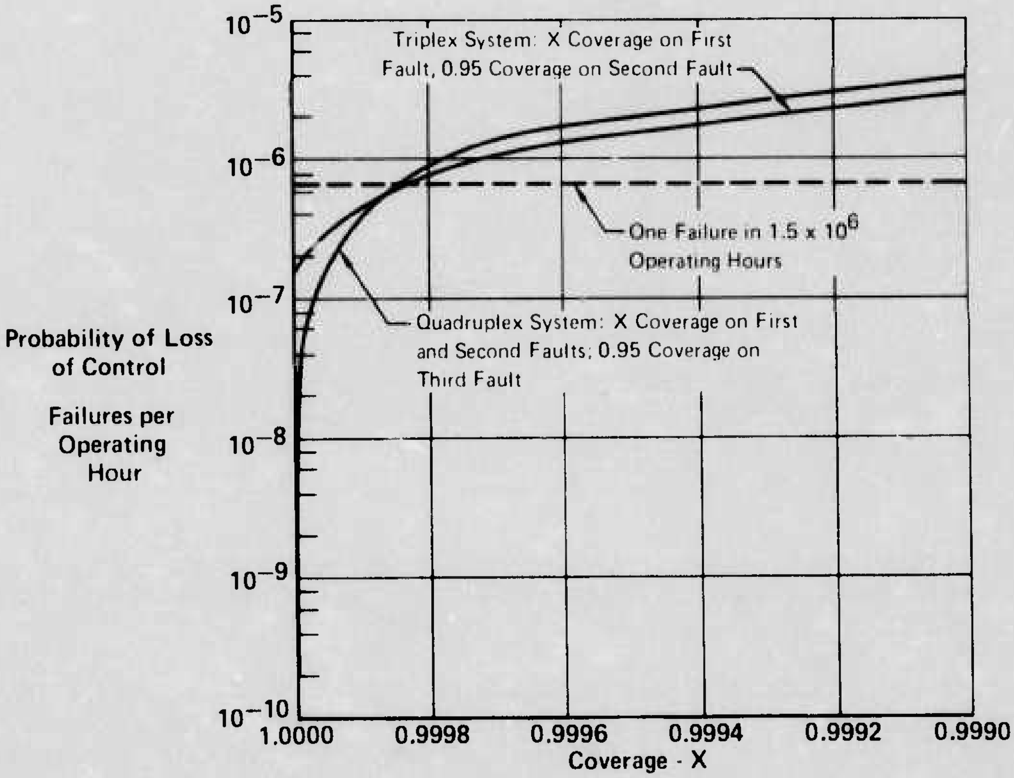
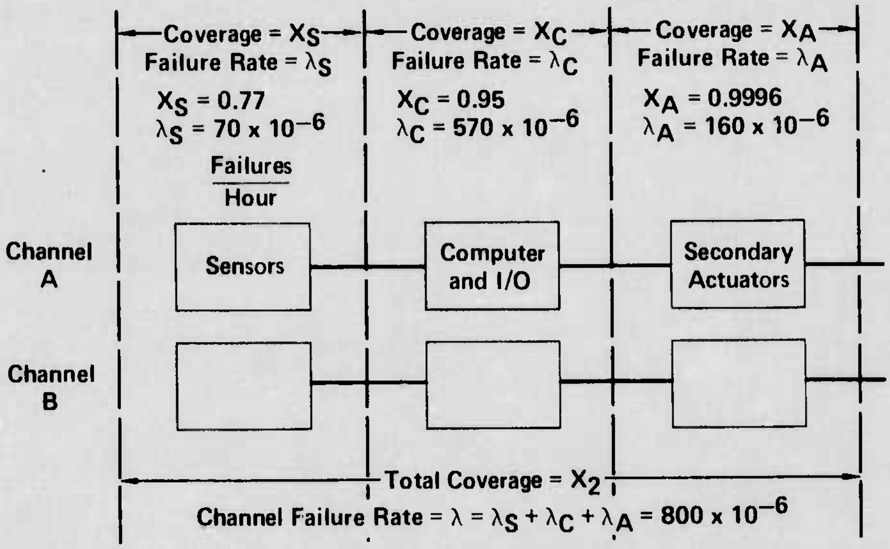


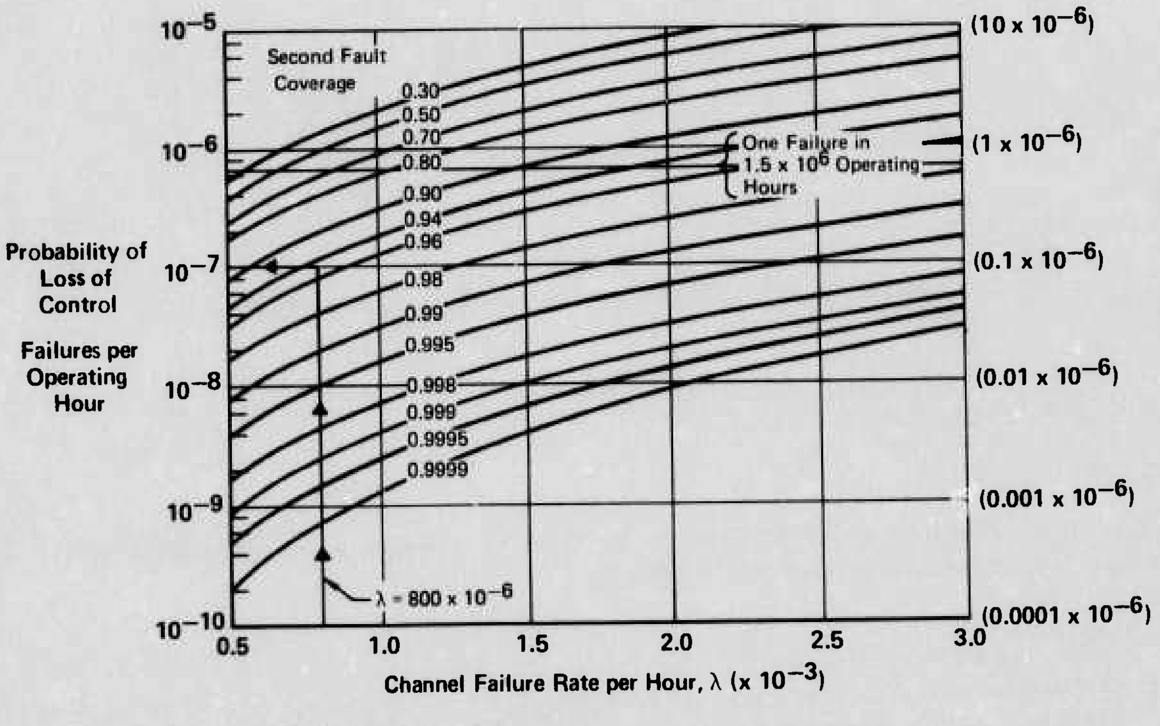
Figure 45
The Importance of Coverage

$$X_2 = \frac{X_S\lambda_S + X_C\lambda_C + X_A\lambda_A}{\lambda} = 0.944$$



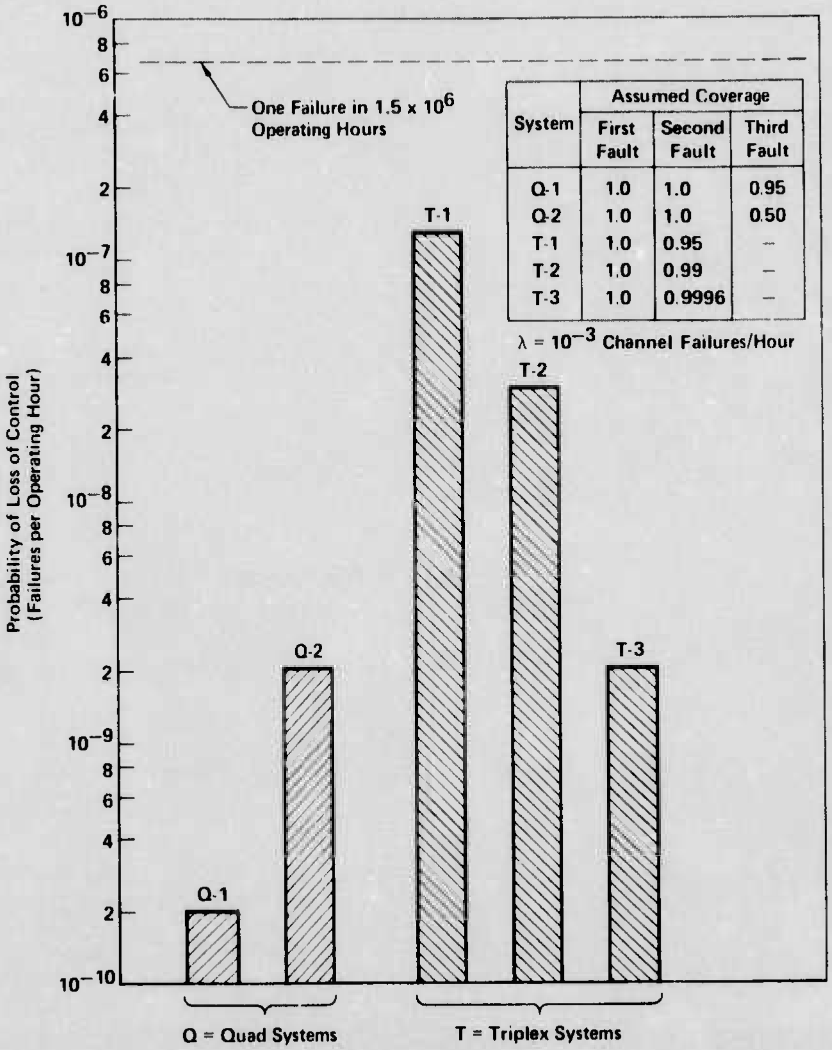
Two-Channel DFCS with Lumped Elements Subject to In-Line Monitoring

Figure 46
Second Fault Coverage (X_2) in a Triplex System



Note: First Fault Coverage = 1.0
Coverage = the Probability of Detecting, Isolating and Recovering from Failures

Figure 47
Triplex System Failure Probabilities



System	Assumed Coverage		
	First Fault	Second Fault	Third Fault
Q-1	1.0	1.0	0.95
Q-2	1.0	1.0	0.50
T-1	1.0	0.95	–
T-2	1.0	0.99	–
T-3	1.0	0.9996	–

Figure 48
Comparison of Quadruplex and Triplex System Reliabilities

2.12.2.2 Distribution of Redundancy Management Functions Among Software, I/O and Actuator Interface Units

Objective

The objective of the study was to define the redundancy management functions to be mechanized in software and in hardware.

Conclusions

- If hardwired cross-strapping of sensors is done (in addition to sensor digital data exchanges), comparison monitoring and signal selection should be done in hardware to keep the computation load down.

- If only data exchanges are used for sensor crossfeed, then the following conclusions are reached:

  - For a quadruplex system, neither a hardware nor a software mechanization shows significant advantages over the other.
  - For a triplex system, the computational load is reasonable and sensor redundancy management should be done in software.

- Secondary actuator monitoring, equalization, and mode engage logic should be done in software to provide hardware savings and ease of fault isolation and preflight self-test.

2.12.2.3 Pre-Sampling Filters for Providing Adequate Input Resolution and Filtering Prior to Digital Data Conversion

Objective

The objective was to determine the applicability of analog prefiltering of sensor outputs.

Conclusions

- First order analog prefilters should be used.
- Use of analog prefilters dramatically reduces sample rate required to provide satisfactory performance with realistic sensor noise and turbulence.
- Minor additional savings can be obtained by using a control law filter as a pre-filter where applicable.

2.12.2.4 Redundancy Degradation with Time

Objective

The objective was to determine the impact of time-dependent failure modes on reliability and on periodic testing requirements. Expressed another way, what failures cannot be detected by BIT and IFIM?

Conclusions

- Undetected failures can have a significant impact on probability of loss of control as shown in Figures 45, 47, and 48.
- BIT and IFIM can detect sufficient failures to make periodic testing unnecessary.

2.12.2.5 Single Point Software Errors

Objective

The objective was to study the feasibility of non-identical programs in redundant channels to preclude single point software errors.

Conclusions

- Non-identical software programs are more costly than a single program.
- Software design, programming standards, verification and control procedures can provide a high degree of confidence that no catastrophic single-point software errors exist.
- A dissimilar channel, e.g., analog or fluidic, is preferable to non-identical software as a means of compensating for single-point software errors.

2.12.2.6 Common Mode, Cascaded and Propagated Failures

Objective

The objective was to assess the probable impact of single-point failures on a fly-by-wire mechanization.

Conclusions

- Single-point failures could be a dominant factor in determining system probability of loss of control (see also Section 2.15).
- Cross-channel monitoring algorithms must be selected with care to prevent cascade-type failures.
- Interconnections between redundant channels should be minimized to limit potential for propagated failures.
- Extreme care must be taken in the design to minimize single point failure probability.
- System configurations with a large number of voting planes increase the potential for common mode failures. This is one of the reasons why it is recommended that the additional voting planes be limited to planes B and C in Figure 49 (see Section 2.12.5) so that data cross-strapping is confined to a single digital data exchange bus which can be properly buffered and monitored.
- High failure detection capability is attainable by BIT and IFIM. Maneuvers, large enough to enable detection of most passive-type sensor failures, will occur during flight. Stimulation of sensors will permit detection of passive-type failures during BIT.

2.12.2.7 Failure Detection for Two-Fail-Operational Capability

Objective

The objective was to determine failure detection probabilities for the three sound candidate configurations.

Conclusions

- Essentially two-fail-op performance of the redundant portion only can be achieved on Configuration C (4-4-4) using cross-channel monitoring and force-summed actuators. No in-line monitoring would be used and the selection of one of two remaining channels would be accomplished by an arbitrary (heads-or-tails) selection of one of the two remaining channels when the 3rd failure occurs. The arbitrary selection has a 0.5 probability of selecting the one good channel and the probabilities for 1st, 2nd, and 3rd failures will be:

  - 1.0 fail-operational;
  - 1.0 fail-operational;
  - 0.5 fail-operational.

- The fail-operational probabilities of the redundant portions of Configuration A (3-3-3), with the coverage numbers given in Paragraph 2.12.2.1 above, and using force-summed actuators to detect first failures and in-line monitoring techniques to detect second failures, will be:
  - 1.0 fail-operational;
  - 0.944 fail-operational.
- Configuration B (4-3-4) improves the fail-op probabilities of Configuration A (3-3-3) only slightly. With perfect second-fault coverage of the sensors and actuators the probabilities will be:
  - 1.0 fail-operational;
  - 0.965 fail-operational.
- One hundred percent two-fail-op performance cannot be achieved using any of the configurations due to the presence of non-redundant components, e.g., surface actuators and control surfaces, and due to the lack of perfect coverage. Therefore, one hundred percent two fail-op should not be a specification requirement; instead, the requirements should be specified in terms of probability of loss of control. The calculation of probability of loss of control should include the entire system and not just the redundant portions. The calculation of probability of loss of control will require knowledge of the probability of occurrence for all single point failures as well as coverage at each level of redundancy.

  A complete specification for probability of loss of control for a flight control system could therefore be simply one requirement in terms of failures per 10^x hours for the entire system. The probability of loss of control could also be specified in terms of channel failure rate, coverage at each level of redundancy, and single point failures.

  For any flight control system there will be trade-offs possible relative to the cost of improving channel failure rate vs the cost of improving coverage vs the elimination of single point failures. The specification of both coverage and failure rate could lead to not achieving the lowest practical probability of loss. Also, specifying both could lead to implementing an approach that is less cost-effective than is possible. For the above reasons it is recommended that the probability of loss of control be specified in terms of one number for the entire flight control system. (i.e. there shall be no more than y failures per 10^x flight hours).

2.12.2.8 Fault Detection and Isolation

Objective

The objective was to determine the significance of in-flight monitoring and failure reporting to the level of a Line Replaceable Unit (LRU) or Weapons Replaceable Assembly (WRA).

Conclusions

- A high level of coverage is essential to the redundant DFCS, as explained in Paragraph 2.12.2.1 above. Coverage is defined as the probability of detecting, isolating, and recovering from faults. Consequently, fault isolation to the degree required to achieve high coverage is essential, and includes isolating failed sensors and controllers, computers, and secondary actuators.
- Fault isolation to the LRU or WRA does not contribute to high fault coverage.
- Fault isolation to the LRU or WRA in-flight is not cost-effective in an ADP and is not recommended.
- Fault isolation to the LRU or WRA is a convenience in troubleshooting during BIT.

2.12.2.9 Nuisance Disconnects and System Reset

Objective

The two objectives of the study were to:

1. Establish criteria for reset by the pilot.
2. Establish criteria relative to nuisance disconnects.

Conclusions

- Analysis indicates that pilot options for resetting certain failures present a potential safety hazard; however, it is planned that a means for resetting all failures will be provided in the ADP. Further experience in the ADP may indicate that reset options should be more restricted in an operational fly-by-wire system.
- Nuisance disconnects of an axis or channel, if specified, should be in terms of a maximum number of occurrences per flight hour not as a ratio of nuisance to actual failures. Tying nuisance disconnects to actual failures implies that a percentage of disconnects shall be actual failures.

2.12.2.10 Computer Instruction Set Requirements for Compatibility with Inputs from Other Airborne Digital Computers

Objective

The object was to determine the flight control computer instruction set requirements for compatibility with inputs from other airborne digital computers, e.g., radar processing, displays, air data, weapons delivery, and automatic landing.

Conclusions

- All inputs to the flight control computers will be by means of program controlled input data busses and direct memory access channels. These means of inputting data require no special computer instruction set requirements.

2.12.2.11 Control System, Display, and Pilot Management Interface

Objective

The objective was to identify the minimum interface required between the pilot and the redundant DFCS to properly and safely implement a redundancy management scheme.

Conclusions

The cockpit controllers for pilot interface are discussed in Section 2.7.

Specifying a ratio of nuisance disconnects to actual failures implies that if you design to permit any nuisance disconnects you must design to cause actual failures.

2.12.2.12 Actuator Servo-Electronics Interface

Objective

The objective was to evaluate the actuator to servo-electronics interface in three different areas: (1) Analog servo command vs digital, (2) Median select vs no median select, and (3) Analog servo loop closure vs digital servo loop closure.

Conclusions

- Based on simplicity of hardware and reduced computation load requirements, the preferred configuration uses:
  - Analog commands
  - No median select and no crossfeed at the secondary actuator
  - Analog loop closure.

2.12.2.13 Failure Modes and Effects Analysis

This topic is discussed in Section 2.16.

2.12.2.14 Hardware Dispersal for Survivability

Objective

The objective was to define and investigate problems resulting from the dispersal of hardware for survivability purposes.

Conclusions

- No reliability problems are associated with the dispersal of computers to enhance survivability, providing the processor and its associated memory are considered as a unit; i.e., located within three feet of each other. This maximum distance requirement is necessary to minimize memory faults due to noise and/or delays in the system logic.

- Nothing is gained by separating the processor from the memory, and the preferred scheme would certainly be to package them both within a single LRU.

- If crossfeeds are required, a digital crossfeed is preferred for hardware dispersal to reduce the interface wiring normally required for analog crossfeeds.

- Accelerometers should not be dispersed because of the differences in accelerations introduced due to different lever arm distances relative to the c.g. Correction by computation may not be practical.

- Structural dynamic differences for the higher control frequencies with dispersed gyros and accelerometers would have to be considered.

2.12.2.15 Module Fault Detection and Repair Verification Through BIT

This topic is discussed in Section 2.11.

2.12.2.16 Degree of Redundancy and Feasibility of Detection and Isolation Techniques

Objective

The objective was to determine the degree of redundancy and feasibility of mechanizing specific failure detection and isolation techniques such as in-line monitoring and cross-channel comparison.

Conclusions

- The quadruplex system requires high coverage on the first and second failures, the triplex requires high coverage on the first failure, as shown in Paragraph 2.12.2.1.

- High coverage is obtained with cross-channel-monitoring, specifically with force-summed secondary actuators, as explained in Paragraph 2.12.2.1 above.

- Third fault coverage in a quadruplex system need not be better than 0.5, which can be achieved in software with a simple "heads or tails" decision.

- Second fault coverage must be moderately high (on the order of 0.95) in a triplex system, as shown in Paragraph 2.12.2.1 above. Second fault coverage is achieved by means of computer self-test and in-line monitoring of sensors and actuators.
- Computer self-test is discussed in Section 2.12.8.
- Sensor in-line monitoring is discussed in Section 2.12.7.
- Actuator in-line monitoring is discussed in Section 2.12.7.

2.12.2.17 Computer Program Synchronization

Objective

The objective was to determine methods for synchronizing redundant computers. The related problems of inter-computer data transfer, actuator command divergence, and sensor processing requirements were considered.

Conclusions

- Frame synchronization of redundant computers is desirable for a number of reasons:
    - Near time-identical samples of redundant sensor signals can be taken, processed, equalized, voted, and a common signal selected for use in subsequent computations in all computers, thereby:
        - Minimizing tracking errors,
        - Preventing channel divergence,
        - Facilitating the detection of failed computers, and
        - Detecting failed sensors.
    - Output commands to secondary actuators can be voted by selecting a common signal and outputting it to redundant secondary actuators.
    - Computer failures can be detected in two ways:
        - By comparing commands and voting a difference which exceeds a specified level, and
        - By the timing-out of a deadman timer.
    - Near-simultaneous mode selection can occur in all computers.
- Frame synchronization can be accomplished in basically two ways: through the use of an external clock(s) that interrupts the computers at the frame rate; or by means of software and a program-loadable timer.
- An external clock(s) requires the minimum software. The clock(s), however, must be mechanized with high reliability. A single clock for all computers would be a potential single point failure.

- A method of synchronizing computers using software and program-loadable timers has been devised based on the following:
  1. Each computer issues a synchronization discrete to itself and the other two computers after it has completed all computations and the cycle time, ΔT, has elapsed, by its own timer. The discrete is reset at the end of each computation cycle.
  2. Each computer monitors synchronization discretes from all computers, beginning at $(\Delta T - \delta)$ and ending at $(\Delta T + \delta)$, where δ is the maximum expected difference between discretes (typically less than 200 μs as measured in the laboratory).
  3. Upon receiving any two synchronization discretes, or when the time $(\Delta T + \delta)$ has elapsed, each computer will begin its next computation cycle.
  4. Once a computer does not recognize two synchronization discretes in three successive computation cycles, it notifies the status panel of its loss of synchronization with the other two computers. (Loss of synchronization does not alter computer operation as described in the previous steps.)
  5. To protect the synchronization process from a discrete failed hard to "1", each computer checks the status of synchronization discretes prior to entering the synchronization interval.
- The synchronization process is designed to incorporate the following features:
  1. Each computer monitors its own synchronization with other computers.
  2. Computer synchronization status is isolated from computer health status.
  3. Each computer continues to cycle, if it is capable, regardless of any indicated failures.
- Intercomputer data transfer, if used, has two main requirements:
  1. Large blocks of data (e.g., sensor data) should be transferred via DMA channels to minimize the duty cycle.
  2. The data transfer must be mechanized so that a failure in the data channel cannot cause the computers to hang up; i.e., the data channel must not be a potential single point failure.
- Actuator command divergence caused by integrators in the forward loop can be eliminated in three ways:
  1. Sensor inputs are exchanged and a common one selected for use in all channels.
  2. Inputs to the integrators are exchanged and a common one selected for use in all channels.
  3. Outputs from the integrators are exchanged and their inputs equalized.

2.12.2.18 Asynchronous Computer Operation

Objective

The objective was to determine the advantages and disadvantages of asynchronous computer operation vis a vis frame synchronous operation (Paragraph 2.12.2.17).

Conclusions

- The advantages of asynchronous operation are:
  - The interface with sensors is simplified.
  - The need for synchronizing algorithms or high-reliability, external clocks is eliminated.
  - The possibility of introducing single point failures is minimized.
- The disadvantages of asynchronous operation are:
  - Large time-skews in sensor data sampling - approaching a full computation frame in the worst case - can occur, requiring wider trip levels in voting and monitoring algorithms, and resulting in larger disengage transients and/or more nuisance disengages.
  - Equalization around forward-loop integrators is required.
  - The effect of transport lags (partially compensated for by high sampling rates) is difficult to assess.
  - Different control modes can exist in different computers for at least one computation frame.

2.12.3 FAULT TOLERANT FEATURES OF SFCS - It is planned that the fault tolerant features of the SFCS will be utilized by retaining the SFCS as a backup to the Digital FCS during initial flights conducted in the ADP.

2.12.4 DIGITAL FCS FAULT TOLERANCE POTENTIAL - The Digital FCS fault tolerance potential will be developed utilizing techniques discussed in Sections 2.12.5 through 2.12.8.

2.12.5 ADDITION OF VOTING PLANES - The inclusion of voting planes is one of the ways by which a redundant flight control system is made fault tolerant. Theoretically, the more voting planes, the more fault tolerant the system. When the system is analog, the addition of voting planes, over and above what are needed to achieve the required system reliability, are costly due to the signal buffering required to prevent fault propagation between channels and the additional dedicated analog voters. With a digital computer, the buffering and cross-channel data transfer are readily facilitated, and the same software voting algorithm can be used to vote on many different signals. Consequently, it becomes practical to consider using many voting planes to increase fault tolerance and improve system reliability.

A study was therefore undertaken to determine the effect of the number and placement of voting planes on system reliability. Figure 49 depicts potential voting plane locations for a typical DFCS.

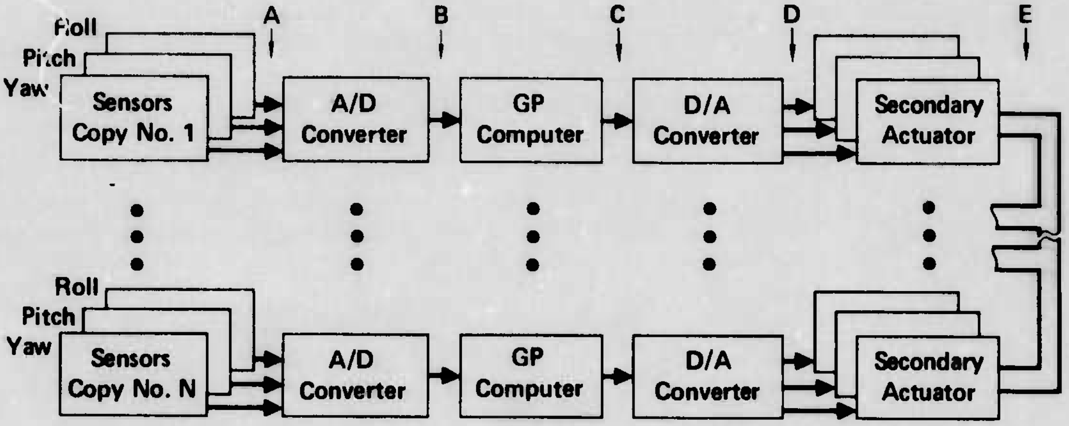


Figure 49
Potential Voting Plane Locations

Table 8 summarizes the results of the study and is constructed using the failure rates given in Table 9. Table 8, from left to right, is arranged in the order of decreasing unreliability (increasing reliability). The parameter used to measure unreliability is the probability of loss of control.

Table 8
The Effect of Voting Planes on DFCS Unreliability

Parameter	Simplex	Triplex	Location of Voting Planes						
			A	D	A&D	B	C	B&C	ABCD
Probability Of Loss of Control (1 Hour Mission)	$1{,}000{,}000 \times 10^{-9}$	1.0×10^{-9}	0.730×10^{-9}	0.730×10^{-9}	0.514×10^{-9}	0.435×10^{-9}	0.435×10^{-9}	0.156×10^{-9}	0.134×10^{-9}

Table 9
Failure Rate Summary

Element	Failure Rate (Per Operating Hour)	Symbol	MTBF (Hr)	Symbol
Sensor*	10×10^{-5}	λ_S	10,000	$\bar{T}_S$
A/D Converters	15×10^{-5}	$\lambda_{A/D}$	6,670	$\bar{T}_{A/D}$
Computer	50×10^{-5}	λ_{COM}	2,000	$\bar{T}_{COM}$
D/A Converters	15×10^{-5}	$\lambda_{D/A}$	6,670	$\bar{T}_{D/A}$
Secondary Actuators	10×10^{-5}	λ_A	10,000	$\bar{T}_A$
1×10^{-3} = Total Channel Failure Rate (λ)				

*The sensors used include a rate gyro, pilot input transducer, and accelerometer, all of which are assumed essential for single channel operation. These failure rates are: Rate Gyro, $\lambda_{RG} = 6.5 \times 10^{-5}$; pilot input transducer, $\lambda_{PIT} = 1.5 \times 10^{-5}$; Accelerometer, $\lambda_{ACC} = 2 \times 10^{-5}$

The sensor failure rate is: $\lambda_S = \lambda_{RG} + \lambda_{PIT} + \lambda_{ACC} = 10 \times 10^{-5}$

In going from simplex to triplex, with a voting plane at E only, and assuming perfect coverage(1), a million to one decrease in unreliability is attained. Adding four additional voting planes ABDC provides a further 7.5:1 decrease in unreliability.

Conclusion

The conclusion that results from this study is that, from a reliability standpoint, there should be a voting plane at E and a maximum of two additional voting planes at B and C. Planes B and C are logical voting planes in the DFCS since the signals at these points are digital, can be exchanged over intercomputer data channels, and can be voted with software algorithms.

---

(1) Coverage = probability of detecting, isolating, and recovering from a fault or failure. See Paragraph 2.12.2.1.

2.12.6 DATA REASONABLENESS - The term data reasonableness was used in the Digital FCS Definition study, to describe a particular in-line-monitoring technique which attempts to identify invalid commands and/or responses by comparing the commands and/or responses with estimated reasonableness models.

The data reasonableness analysis was conducted by identifying the parameters associated with pilot-assist modes and pilot-relief modes which could be critical to ground and/or flight safety.

Having identified the parameters associated with pilot-assist and pilot-relief modes which have the highest potential for implementing safety by applying data reasonableness techniques, the maximum, minimum and maximum rate of change of these parameters was estimated. The estimates are presented in Table 10.

Table 10
Data Reasonableness Parameter Estimates

Candidate Parameter	Source	Value		
		Maximum	Minimum	Maximum Rate of Change
Velocity	CADC	1600 mph	0	32 ft/sec^2
Altitude	CADC	60,000 ft	−200 ft	+1400 ft/sec, −1400 ft/sec
Altitude Rate	CADC INS	+1400 ft/sec	−1400 ft/sec	290 ft/sec^2
Mach	CADC	2.2	0	0.12/sec
Pitch Angle	INS AHRS	N/A (360° loop possible)	N/A (360° loop possible)	80°/sec
Bank Angle	INS AHRS	N/A (360° roll possible)	N/A (360° roll possible)	300°/sec
Mass (Fuel flow only)	Fuel System	56,000 lbs	34,000 lbs	12,000 lb/hr for fuel
Density	CADC	0.003 slugs/ft^3	0	$6 \times 10^{-5} \frac{\text{slugs/ft}^3}{\text{sec}}$
Side Slip Angle	Side Slip Probe	+15°	−15°	80°/sec
ACL Pitch Command	AN/ASW-25A	+13.5°	−13.5°	8°/sec
ACL Roll Command	AN/ASW-25A	+14°	−14°	15°/sec
Dynamic Pressure	Dynamic Pressure Sensor	2100 lb/ft^2	0	$200 \frac{\text{lb/ft}^2}{\text{sec}}$

CADC- Central air data computer
INS- Inertial navigation system
AN/ASW-25A - Digital data communications set
AHRS - Attitude - heading reference system
ILS - Instrument landing system

Additional data reasonableness concepts were studied and are in References (12) and (22).

References: 12. Digital Flight Control System Study Final Report, ACS 10,713, General Electric Co., Binghamton, N.Y. October 1974.

22. Advanced Fighter Digital Flight Control System (DFCS) Definition Study - Final Report, W0728-FR, Honeywell, Minneapolis, Minnesota. March 1975.

Conclusion

- o It is planned that the values presented in Table 10 will be stored in the memory of the flight control digital computers and used to aid in validating the parameters prior to use in flight control mode computations. The values in the table may require refinement during implementation in the ADP.
- o Consideration will also be given to some of the schemes presented in References (12) and (22).

2.12.7 IN-LINE MONITORING OF SENSORS AND ACTUATORS - The ability of the Digital FCS to reconfigure itself and continue undegraded operation when a fault occurs in one of two remaining channels is implemented using in-line monitoring.

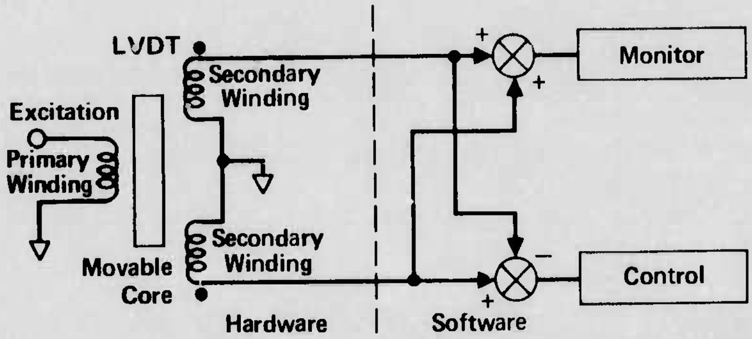
The fault recognition scheme applied during the Digital FCS Definition Study is presented in Figure 50.

- Determine Failure Modes
- Determine Symptoms Associated with the Failure Modes
- Design Tests to Detect Symptoms
- Implement Tests in Hardware or Software

Figure 50
Fault Recognition Scheme

Initial efforts relative to in-line monitoring of sensors and actuators were characterized by an attempt to develop fault recognition schemes which yielded 100% fault coverage. This activity was motivated by an attempt to achieve perfect two-fail-operate performance using three channels. The initial objective did not prove to be feasible, as summarized below; however, adequate in-line monitoring schemes were designed.

The analysis indicated that virtually 100% coverage of all known failure modes of Linear Variable Differential Transformers (LVDT's) could be obtained by the scheme illustrated in Figure 51. It is planned that the LVDT monitor illustrated will be implemented by software in the Digital Flight Control Computer (DFCC).



The output of the secondary windings is summed and compared with a reference voltage. During normal operation the sum of the voltages is constant. The control signal is the difference between the outputs of the two secondary windings.

Figure 51
Linear Variable Differential Transformer (LVDT) Monitor

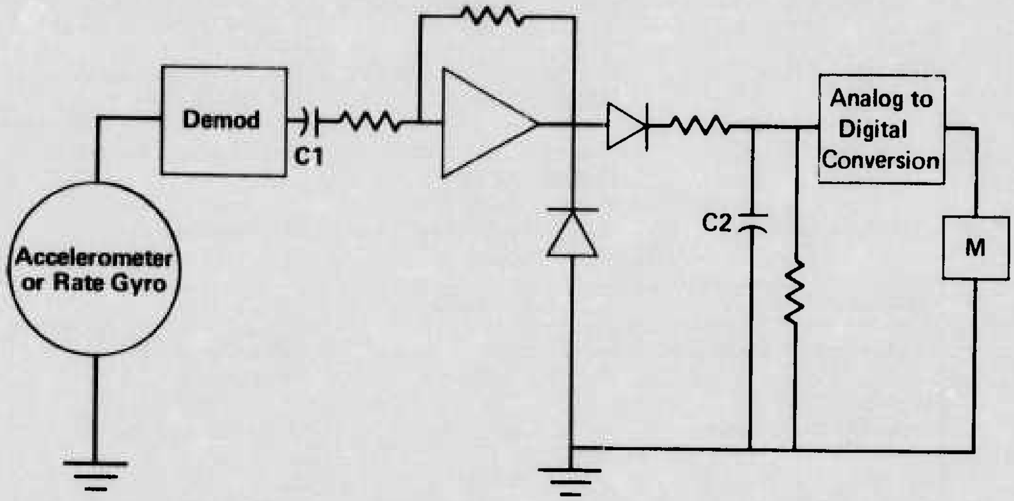
The analysis indicated that 97% of known failure modes of the accelerometers installed in F-4 S/N 62-12200 could be detected by two rather simple in-line detection schemes as illustrated in Table 11. The "extended range" test consists of comparing the accelerometer output (magnitude) with a maximum allowable value. It is planned that the accelerometer extended range test will be implemented by software in the DFCC. The AC Voltmeter Type Circuit is a circuit which detects oscillating outputs with frequencies substantially above the control frequency. This circuit is illustrated in Figure 52. Implementation of this test requires hardware to detect the AC content of the signal. The monitoring can be accomplished by software in the DFCC and it is planned that it will be done in this manner.

Table 11
In-Line Monitoring of Accelerometers

Failure	Symptoms	In-Line Detection Scheme
Oscillator Degradation	Hard Over Output Voltage	Extended Range
Null Shift	High Null	None
Bearing Friction or Failure in Moving and Restoring System*	Sticky or Ratchety Output Voltage	None
Capacitor Failure	Output Oscillates at 300 Hz	AC Voltmeter Type Circuit

*In-Flight Vibration Reduces Probability that this Failure will Occur In-Flight

Monitors 97% of Known Failures



The AC component passes through C1, is rectified and charges C2. If the voltage across C2 exceeds the predetermined level the monitor will trip.

Figure 52
AC Voltmeter Type Circuit

The analysis indicated that only 74% of the failure modes of the SFCS rate gyros installed in F-4 S/N 62-12200 could be detected by in-line detection schemes as illustrated in Table 12. The extended range test and AC Voltmeter Type Circuit are equivalent to the tests discussed above for application to accelerometers. The Motor Current Monitor and Spin Motor Rotation Detector (SMRD) tests are illustrated in Figures 53 and 54 respectively. Implementation of the tests again requires both hardware and software. It is planned that the necessary hardware will be provided in the DIF and that the monitoring function will be accomplished by software in the DFCC.

Table 12
In-Line Monitoring of Rate Gyros

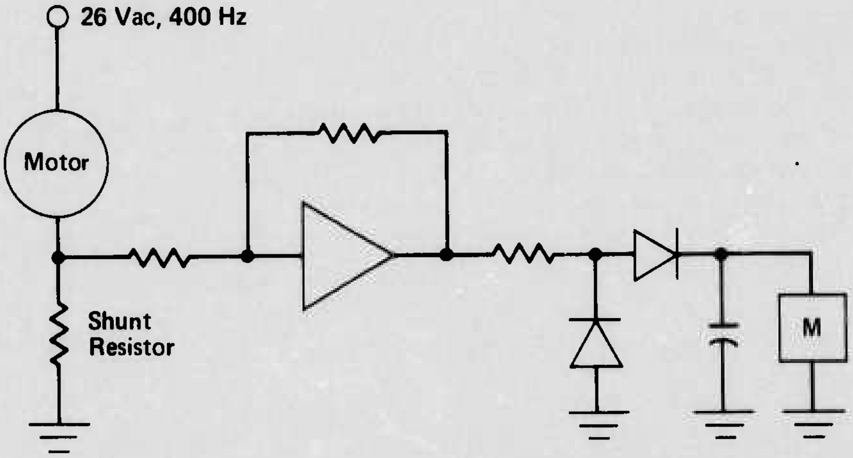
Failure	Symptoms	In-Line Detection Scheme
No Start or Stop	High or No Motor Current No SMRD Output	Motor Current Monitor and SMRD
Slow Start	Starting (High) Current Present Too Long	Motor Current Monitor
No Synchronization	High Motor Current, Low SMRD Output	Motor Current Monitor
Null Shift	High Null Voltage	None
Failed Output Transducer	No Output, Hardover Output	Offset Transducer* Extended Range
High Starting Current	Current Above Normal During Start	Motor Current Monitor
Erratic Output	Varying Output Voltage	AC Voltmeter Type Circuit
Damping Fluid Problems	Change in Damping	Torque Tests

Based on information from Northrop - sample base of 22,000 rate gyros

SMRD - spin motor rotation detector

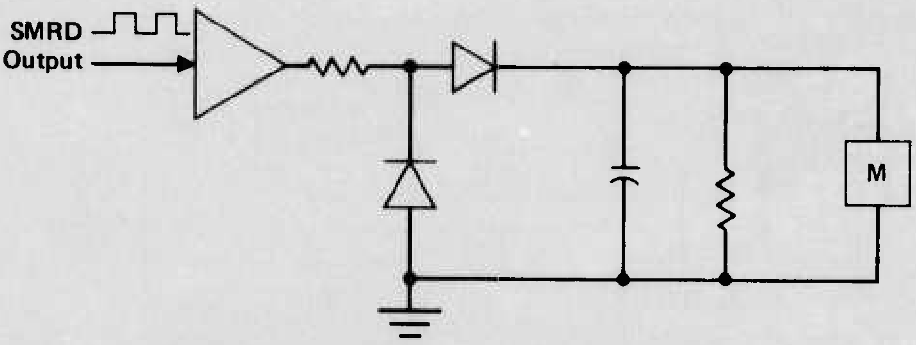
*The SFCS rate sensors would require modification to provide offset transducers and an additional 3% of failures could be detected.

Monitors 74% of Known Failures



The monitor is a window circuit. If the shunt voltage is within the window it is correct.

Figure 53
Motor Current Monitor



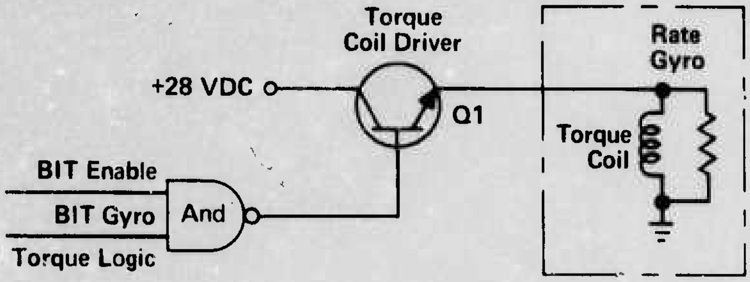
The output pulses are amplified and will charge up the capacitor. As the wheel slows down the charge on the capacitor will decrease below the monitor trip level.

Figure 54
Spin Motor Rotation Detector
(SMRD)

The Torque Test circuitry, illustrated in Figure 55 is planned to be used only to apply a stimuli to the rate gyro during preflight BIT.

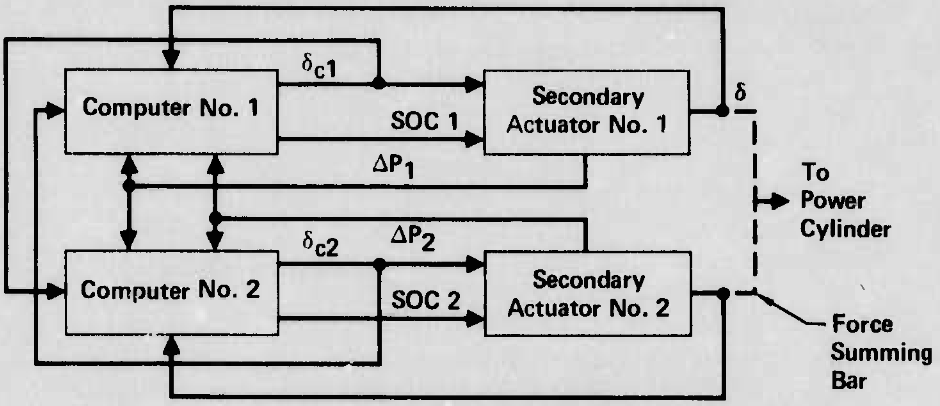
The analysis indicated that 99.96% of known secondary actuator failures could be detected when two secondary actuator elements remained. The fault detection scheme is illustrated in Figure 56. It is planned that the monitoring will be accomplished by software in the DFCC's. The 90-word algorithm planned for this application is presented in Figure 57.

Additional in-line monitoring concepts were studied and are in References (12) and (22).



During BIT the "BIT enable" is applied to the And gate. When the gyro is to be torqued the "BIT gyro torque logic" discrete is applied to the And gate. The And gate changes states and turns on transistor Q1 applying +28VDC to the rate gyro torque coil.

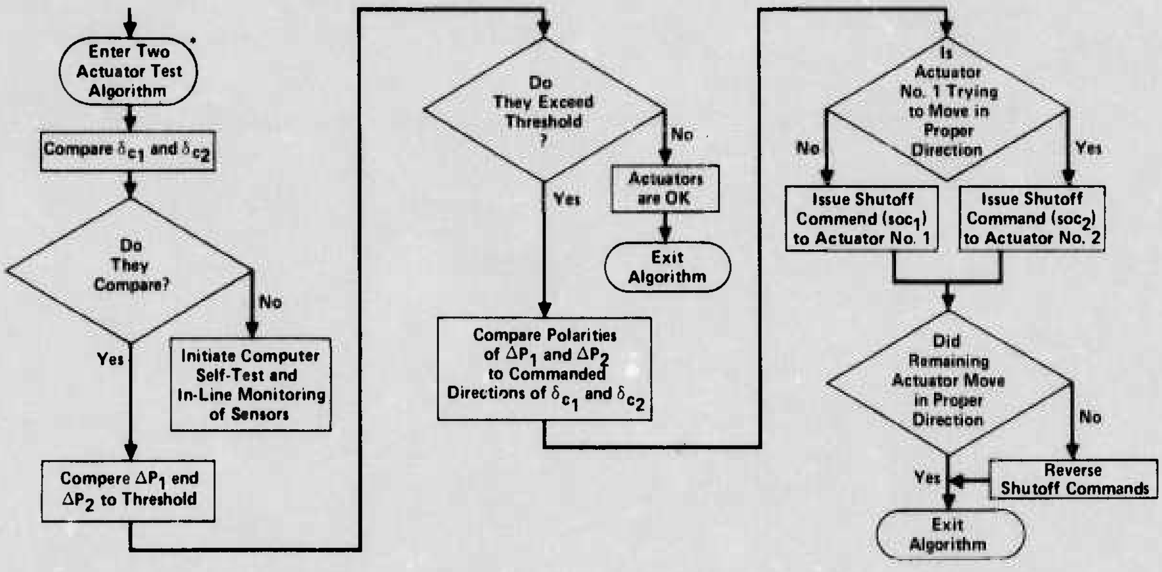
Figure 55
Torque Test Circuitry
(Stimulus Test)



δ = Secondary Actuator Position
δ_c = Secondary Actuator Commanded Position
ΔP = Differential Pressure
SOC = Shut-Off Command

Monitors 99.96% of Known Failures

Figure 56
In-Line Monitoring of Secondary Actuators



Algorithm Size = 90 Words

*Preconditions
1. Two actuators remain
2. The computers receive secondary actuator position, δ
3. The computers receive differential pressure signals, ΔP_1 and ΔP_2
4. The computers exchange actuator commands, δ_{c_1} and δ_{c_2}

Figure 57
Algorithm for Detecting which of Two Actuators Has Failed

Conclusions

The analysis indicates that the fault coverage which can be achieved by in-line monitoring techniques varies from 74 to over 99 percent for the sensors and actuators.

While this coverage is not sufficient to provide 100% "two fail operate" performance using three channels, the redundancy management, safety and reliability analyses, using the in-line monitoring results summarized above, do indicate that the safety and reliability goals of the Digital FCS Definition Study can be achieved.

2.12.8 DIGITAL COMPUTER SELF-TEST

2.12.8.1 General - After one failure in a triplex system and two failures in a quadruplex system, in-line monitoring must be used to resolve any channel differences if the DFCS is to continue to operate. When in-line monitoring is used, the computer must first test itself; then it is in a condition to check other elements of the DFCS.

2.12.8.2 Self-Test Features - Self-testing of digital computers involves a mix of hardware and software. Certain basic portions of the computer must be operable before any self testing can be conducted, e.g., power supplies and clocks. Failure of these basic portions must be detected by hardware.

With these basic portions of the computer operating, self-testing of the computer can begin. The design of the self-test program is based on the inverted pyramid test philosophy. That is, the program first tests the instructions that require a minimum of logic for their execution, and the memory locations that contain the self-test program. These verified instructions and memory locations are then used to test instructions and memory on the next higher level. This process is continued until all of the instructions, memory, and I/O have been verified.

Studies conducted at MCAIR have indicated that the self-test procedure should include the following features:

(1) Hardware circuitry will be used to monitor the computer power supplies. Power supply status signals will be exchanged between computers.

(2) A high-priority power failure interrupt will be incorporated to effect an orderly computer shut-down in the event of a power drop-out. Power-off and power-on status signals will be exchanged between computers.

(3) A deadman timer (redundant if necessary to achieve required reliability) will be incorporated to detect computer stoppages. Failure of the software to reset the timer indicates a computer failure. This computer fail signal will be sent to a status panel and to the other computers.

(4) An interval timer will be used to monitor the time required to complete various portions of the self-test program.

(5) Parity will be used to continuously monitor the memory storage locations. When bad parity is indicated an interrupt will be initiated.

(6) Data, address, and control lines will be checked by reading out of memory data patterns of zeros and ones, stored in predetermined locations.

(7) Memory-sum checks will be used to check those portions of memory containing constants and instructions. Since the sum check requires more execution time than can be spared during normal DFCS operation, the sum-check will only be used immediately following computer start-up.

(8) The CPU will be checked by means of sample problems, designed to exercise the instructions used to solve the control laws.

(9) An arithmetic fault interrupt will be used to sense overflows.

(10) I/O functions will be checked by wrapping the output and input channels.

(11) Parity will be used to continuously monitor the transmission of data over the I/O channels. When bad parity is detected, an interrupt will be initiated.

2.12.8.3 Software Required for Computer Self-Test - The software required to carry the computer self-test is estimated to require 1000, 16-bit words.

2.12.8.4 Failure Detection Probability of Computer Self-Test - Current airborne computers are specified to have a probability of detecting failures of 0.95. The probability of detecting failures is frequently called "confidence factor" (γ). The manufacturers of these computers indicate that they can meet this confidence factor.

The confidence factor, γ, is usually determined by the formula:

$$\gamma = \frac{\lambda_0 + \lambda_2}{\lambda_{total} - \lambda_3} \tag{1}$$

where

λ_0 = Failure rate of parts whose failure causes the loss of the computer but provides failure indication.

λ_1 = Failure rate of parts whose failure causes the loss of the computer but does not provide failure indication.

λ_2 = Failure rate of parts whose failure causes no loss of the computer but provides failure indication.

λ_3 = Failure rate of parts whose failure causes no loss of the computer but does not provide failure indication.

$\lambda_{total} = \lambda_0 + \lambda_1 + \lambda_2 + \lambda_3$

Computer manufacturers usually conduct a Failure-Mode-and-Effects Analysis (FMEA) to segregate the piece-part failures into the failure categories required in Equation (1).

The confidence factor is usually limited to 0.95 by the fact that portions of the computer I/O cannot be checked. Studies at MCAIR have indicated that, if I/O wrap-around tests are performed so that the I/O can be checked, the confidence factor can be raised to 0.995.

Studies conducted at General Electric (Reference (12)) have concluded that a typical airborne computer is likely to contain 10,000 to 20,000 single failure modes, making an exhaustive FMEA an insurmountable task. Reference (12) reports a statistical approach that evaluates the confidence as to the lower limit of γ based on the undetectable failures that are observed in a given test sample size. It was concluded that γ values in the range of 0.90 to 0.95 are possible.

Another approach to the assessment of the probability of detecting failures is believed to be more applicable to the DFCS. For the DFCS application, the computer is functioning properly if it is capable of performing all necessary computations and data transfer operations. These operations in a DFCS application are very limited in number. The self-test hardware and software should be designed to determine whether the computer is functionally able to perform these operations, and not which computer component may have failed. For example, one of the operations the computer must perform is to cycle through all the instructions in the program. Failure to do so means that the computer has stopped (a high percentage of computer failures are of this type). This condition can be easily detected with a watch-dog timer. Note that for DFCS in-line monitoring, it is not necessary to know precisely which failed part causes the computer to stop. Following this line of reasoning, Equation (1) can be rewritten as,

$$\gamma = \frac{\text{The Number of Erroneous DFCS Operations That Can Be Detected}}{\text{The Total Number of DFCS Operations}} \qquad (2)$$

In view of the above, it is believed that using $\gamma = 0.95$ in present reliability studies is conservative. A self-test program that incorporates the features itemized above, when evaluated by Equation (2), will yield a γ considerably higher than 0.95.

2.12.8.5 Conclusions - From the analysis of computer self-test, it is concluded that:

- The confidence factor, without a complete I/O test, is on the order of 0.95 when evaluated by Equation (1);
- The confidence factor, when a complete I/O wrap test is incorporated, is on the order of 0.995 when evaluated by Equation (1);
- The confidence factor, when evaluated by Equation (1), is difficult to calculate through a FMEA, and even more difficult to demonstrate in the laboratory, because of the large number of piece-part failure modes;
- With the self-test features of 2.12.8.2, it should be possible to demonstrate by Equation (2) a confidence factor considerably greater than 0.95.

2.13 ANALYSIS OF INDUSTRY EXPERTISE

During the past several years a large amount of general foreground research in digital flight control and display technology has been accomplished. A list of more than seventy-eight technical documents reporting both this work and programs currently in progress was prepared and the documents were reviewed prior to and during the Digital FCS Definition Study. The information contained in the documents was used, where applicable, in the analyses, simulations and ADP definitions.

Continuing contacts with the computer and flight control industries have kept MCAIR informed of the fast developing technology in digital flight control design.

Subcontracts were placed with four selected equipment manufacturers and the work done by these subcontractors is summarized in Figure 58. See also Section 5.0.

The work of the above subcontractors is presented in References (12), (15), (22), and (23).

General Electric ● Digital Implementation of Control Laws ● Data Reasonableness ● In-Line Monitoring of Sensors and Actuators ● Computer Reliability, Redundancy and Self-Test ● Lab Demonstration of 3 Computers Operating Synchronously	**Honeywell** ● Digital Implementation of Control Laws ● Data Reasonableness Concept Investigation ● In-Line Monitoring Concept Investigation ● Redundancy and Reliability Concept Investigation ● Pilot - Computer Communications
Collins ● Pilot-Computer Communications ● Provide Area Nav and CDC for Simulation	**Lear Siegler Incorporated** ● Digital Computer Self-Test ● Redundancy Management ● Lab Demonstration of 2 Computers Operating Asynchronously

Figure 58
Work Done by Four Selected Subcontractors

References:

12. Digital Flight Control System Study Final Report, ACS 10,713, General Electric Co., Binghamton, N. Y. October 1974.

15. Digital FCS Study Final Report, 523-0766085-00111M, Collins Avionics Division, Rockwell International, Cedar Rapids, Iowa. 15 February 1975.

22. Advanced Fighter Digital Flight Control System (DFCS) Definition Study - Final Report W0728-FR, Honeywell, Minneapolis, Minnesota. March 1975.

23. Advanced Fighter Digital Flight Control System Study - Final Report (Draft) ADR-789, Lear Siegler, Inc., Astronics Division, Santa Monica, California. April 1975.

2.14 SOFTWARE ANALYSIS

Analyses have been conducted to estimate the software requirements for the candidate ADP configurations.

2.14.1 MULTIMODE CONTROL LAWS

2.14.1.1 Memory Required - An evaluation of the memory required for each of the control laws discussed in Section 2.4 is summarized in Table 13.

Table 13
Memory Requirements for DFCS Control Laws

Mode	Memory (Words)	
Normal Mode		1,067
Lateral-Directional	426	
Longitudinal	641	
Air-to-Ground Gun Mode(1)		1,141
Longitudinal	285	
Lateral-Directional	856	
Air-to-Ground Bombing Mode(1)		
Lateral-Directional	720	720
Longitudinal (Same as Normal Mode)	0	
Air Combat Mode(1)		200
Manual Carrier Landing(1)		
Longitudinal	239	790
Lateral-Directional	267	
Pitch Rate Autothrottle	284	
Automatic Carrier Landing(1)		
Longitudinal	162	410
Lateral-Directional	248	
Pitch Rate Autothrottle (Same as Manual Carrier Mode)	0	
Pilot Relief Modes		854
Altitude and Pitch Attitude Hold	355	
Heading and Roll Attitude Hold	361	
Mach Hold	138	
Energy Management Control(1)		203
Departure Prevention		593
Departure Preventer	528	
Longitudinal Pre-Filter	65	
Fixed Canards (Same as Longitudinal Normal Mode)		0
Total		5,978

(1) Excludes Complementary Programs Performed in Display Computer

The Normal Mode is treated as the basic program; the other modes are then treated as "add-ons". For example, the Air-to-Ground Gunnery Mode uses some of the same transfer functions as the Normal Mode; consequently, the memory required for the Air-to-Ground Gunnery Mode includes only those functions not already provided by the Normal Mode. Functions are never duplicated. For example, the memory required by the Automatic Carrier Landing Mode includes only those functions not already provided by the Manual Carrier Landing Mode.

The memory requirements shown in Table 13 are for the flight control computers only, and exclude certain basic computations performed in the display computer. The air-to-ground mode requirements, for example, do not include the solution of the ballistic equations, which are solved in the display computer.

2.14.1.2 Control Law Digitization - One widely-used approach to designing digital filters can be classified as digitally simulating a continuous (or "analog") filter. This approach uses a transformation method which transforms the continuous filters that comprise the control laws into difference equations which are solved by the digital flight control computers. The resulting difference equation mimics the continuous filter in the frequency domain.

Of the man transformation techniques, the Tustin Bilinear Transformation is recommended since it is easy to use and understand, preserves stability, allows cascading of filters, and has the same system order and d-c gain. The property of cascading is very important to the digital implementation of control laws that have been partitioned into modular software.

The primary deficiency of the Tustin Transformation is that it does not preserve the impulse response. For DFCS applications, this deficiency manifests itself primarily in a shift in the notch frequency of bending-mode filters. This deficiency can be satisfactorily overcome by prewarping the analog poles and zeros. The Tustin Transformation is discussed in Reference (24) as well as elsewhere in the literature.

2.14.1.3 Direct Digital Design - The quality of a digital transformation is judged on the ability to match the analog filter without consideration of the original performance specification. Direct digital design presumably overcomes this restriction by allowing direct digital synthesis in either the W or Z planes.

In many practical applications, a satisfactory analog controller is designed to meet an original performance specification. In this case, a transformation technique is appropriate since it is easier to compare performance related to the analog controller than to start over with a direct digital design to some original performance specification. The original performance specification is probably lost anyway through the typical iterations and modifications of a flight test program which has "optimized" performance.

The issue of "direct" versus "transformation" becomes somewhat of a moot point since any Z transfer function has an analog counterpart for a given conversion technique. Given sufficient understanding of the distortion produced by a particular conversion, proper adjustments in the analog form may be made for compensation. Either technique can provide a satisfactory digital design with little effect on required computer resources. For higher frequency functions, the direct selection of discrete parameters results in better performance in terms of specified frequency response.

2.14.2 REDUNDANCY MANAGEMENT AND/OR IFIM

2.14.2.1 Memory Required - An estimate has been made of the memory required to implement a redundancy management system. The redundancy management system consists of a number of in-line monitoring and cross-channel comparison techniques. The software routines that carry out these techniques are termed Redundancy Processing. The amount of redundancy processing required is different for a triplex or quadruplex system. Redundancy processing requirements are shown in Table 14.

Reference: 24. Technical Report AFFDL-TR-73-119, Volumes I, II & III "Digital Flight Control Systems for Tactical Fighters", Honeywell, Inc., July 1973.

Table 14
Memory Requirements for Redundancy Management and/or IFIM

Function	Memory	
	Triplex	Quad
Signal Selection Algorithms	1450	2800
Fault Recovery Routine	200	200
Computer Self-Test (Includes Partial DIF)	1000	0
In-Line Monitoring of Rate Gyros and Accelerometers	30	0
In-Line Monitoring of Secondary Actuators	270	0
In-Line Monitoring of Single and Duplex Sensors	300	300
Synchronization Routine	100	100
Subtotal	3350	3400

The Selection Algorithms memory requirements shown in Table 14 is based on the use of the algorithms to signal select on 14 sensor inputs and 11 surface commands; however, if sensor signal selecting is eliminated, the signal selection memory requirement will be reduced by 56%.

Following detection of a faulty channel, or a faulty unit within the channel, it is necessary to reconfigure the remaining good units and channels so that the DFCS can continue to function. The Fault Recovery Routine required to effect this reconfiguration is estimated to require 200 words.

The computer self-test routine, used for in-line monitoring in the triplex DFCS was discussed in Section 2.12.7. It is estimated to require 1000 words. It is assumed to be required in the triplex DFCS only, since the quadruplex DFCS achieves adequate reliability without in-line monitoring.

Reference (24) outlines techniques for in-line monitoring of rate gyros and accelerometers that require 6 words per unit. Since there are 3 rate gyros and 2 accelerometers per channel, 30 words would be required.

Reference (24) outlines a technique for in-line monitoring of hydraulic secondary actuators. The software algorithm, consisting of an actuator model (60 words) and equalization logic (30 words) requires 90 words per actuator. It is assumed that the algorithm can be used as a subroutine for identical actuators, e.g., the left and right ailerons, but must be repeated for different actuators, e.g., the canard and stabilator. If it is then assumed that there are three non-identical actuators, i.e., canards, throttle, and all other control surfaces, 270 words will be required.

Signals from sensor sources that are typically less than triply redundant, e.g., CADC's, INS's, attitude gyros, data links and display computers, must be treated on an individual basis to determine their validity. In some cases, validity discretes from the signal source are sufficient to indicate the validity of the signal. In other cases, two identical or similar signals can be compared, and if they discompare by more than a certain amount, both signals can be ignored. In still others, various types of reasonableness tests can be used. The treatment of these types of signals, labeled In-Line Monitoring of Single and Duplex Sensors, is estimated to require 300 words. These signals must be monitored in the quadruplex as well as the triplex DFCS to protect the gain schedules and outer-loop commands.

The routine required to synchronize the computers is estimated to require 100 words.

2.14.3 BIT

2.14.3.1 Memory Required - The memory requirement for implementation of the preflight BIT has been estimated. The memory required to implement the BIT program segments is given in Table 15.

Table 15
Memory Required to Implement the BIT Program Segments

Program Segment	Memory	
	Triplex	Quadruplex
Computer Self-Test	0*	1000
Power Supply Tests	100	100
Switch Tests	200	200
Sensor Tests	500	500
Actuator Tests	200**	470
Digital Interface Tests	600	600
BIT Subexecutive	100	100
Display Routine	300	300
Subtotal	2000	3270

* 1000 Words of Computer Self-Test are Used for Second-Fault Redundancy Management and are therefore Accounted for.

** 270 Words of Actuator Tests are Used for Second Fault Redundancy Management and are therefore Accounted for.

The memory required to implement computer self-test, used for in-line monitoring in a triplex system, is 1000 words. Since the self-test routine used in BIT is essentially the same as that used for in-line monitoring in the triplex system, the memory required has already been accounted for in the case of the triplex system.

The power supply tests are estimated to require 100 words.

The switch tests are estimated to require 200 words. The switch tests may require some portions of the mode switching logic (2400 words total), but this memory has already been accounted for as an executive function.

The sensor tests are estimated to require 500 words.

The actuator tests are estimated to require 270 words of memory (used for in-line monitoring in a triplex system) plus an additional 200 words to test the actuator isolation devices at different redundancy levels. These additional tests will cause a force fight at the secondary actuators, simulating an actuator failure or channel fault, thereby testing the ability of the device to isolate a fault. The 270 words has already been accounted for in the case of the triplex system.

The Digital Interface Unit (DIF) is estimated to require 600 words. The memory required for this unit depends on the level of fault isolation required. The 600 words assumes fault isolation to a function.

The BIT subexecutive, which controls and links the various program segments is estimated to require 100 words.

The Display Routine, which formats the various messages on the CDC, is estimated to require 300 words.

2.14.4 MUX - The MUX system, discussed in Section 3.2.7, has no impact on the flight control computer.

2.14.5 EXECUTIVE

2.14.5.1 Memory Required - The memory required to implement the executive functions of the flight control computers is summarized in Table 16.

Program initialization estimated requirements are shown in Table 17. The memory sum test would not be required in a quadruplex system.

Table 16
Executive Memory Requirements

Function	Memory	
	Triplex	Quadruplex
Program Initialization	450	300
Interrupt Processing	620	620
Program Scheduling	100	100
Input/Output Processing	420	420
Mode Switching Logic	2400	2400
Total Executive	3990	3840

Table 17
Program Initialization

Function	Memory	
	Triplex	Quad
Variable Initialization	300	300
Memory Sum Test	150	–
Subtotal	450	300

2.14.5.2 Interrupt Processing - The function of interrupt processing is to service all internal and external priority interrupts. Table 18 breaks down the memory requirement by interrupt processing function.

2.14.5.3 Program Scheduling - Program scheduling involves scheduling the modules in the proper time sequence and the background programs on a computer-available basis. The program scheduling function is estimated to require 100 words.

Table 18
Interrupt Processing

Function	Memory Quad and Triplex
Power Fail Interrupt	50
Write Protect Interrupt	70
Memory Parity Error Interrupt	60
I/O Channel Parity Error Interrupt	70
Arithmetic Fault Interrupt	50
Deadman Timer Interrupt	10
Internal Timer Interrupt	40
External Spare Interrupt	50
Computer Control Panel Interrupt	20
End-of-Frame Processing	100
DMA Transfer Complete Processing	100
Subtotal	620

2.14.5.4 Input/Output Processing - Input/Output processing estimated requirements are shown in Table 19. The Control Panel Processing function handles the packing, unpacking, coding, and decoding associated with reading data into and out of the control computer via a control panel. The Sensor Data Preprocessing function includes the digital data processing that precedes signal selection, and includes, for example, removing sensor reference voltage variations. The DMA channel control routine initiates and terminates data flow over the DMA channel.

Table 19
Input/Output Processing

Function	Memory Quad and Triplex
Control Panel Processing	200
Sensor Data Reprocessing	200
DMA Channel Control	20
Subtotal	420

2.14.5.5 Mode Switching Logic - Reference (24) gives the memory required to implement the engage logic for a SAS, CAS, and Autopilot control system. The autopilot discussed in Reference (24) has only an attitude hold mode. The engage logic, including priority logic, faders, and synchronizers, requires approximately 600 words. The multimodes of the DFCS are estimated to require four times this number or 2400 words. Obviously, the estimate is heavily dependent on the actual number of modes implemented in the ADP.

2.14.6 TOTAL FLIGHT CONTROL MEMORY - The total memory estimates for the Triplex and Quadruplex Flight Control Computers presented in Sections 2.14.1 through 2.14.5 are summarized in Table 20.

Table 20
Total Memory Required for Flight Control Computers

Category	Memory	
	Triplex	Quadruplex
Control Laws	6,000	6,000
BIT	2,000	3,270
Redundancy Management and/or IFIM	3,350	3,400
Executive	3,990	3,840
Total	15,340	16,510

2.14.7 <u>DISPLAYS AND CONTROLLERS - MEMORY REQUIRED</u> - The displays and controllers configuration to implement the DFCS ADP is given in Section 4.4. The block diagram (Figure 96, Section 4.4) includes a display computer and a flight management computer. The memory required for the Display Computer, but not the Flight Management Computer, is given in Table 21.

Table 21
Memory Requirements for Display Computer

Module	Memory Words (16 Bits)
Executive	840
Data Base	2,600
Subroutines	740
Self-Test	820
Navigation	2,960
Air-to-Ground	2,630
Air-to-Air	3,660
Flight Director	590
Controls and Displays	2,340
Radar Target Generation	7,000
Total	24,180

2.15 SINGLE-POINT-FAILURE ANALYSIS

2.15.1 GENERAL - A single-point-failure analysis was performed during the early stages of the Digital FCS configuration selection. The purpose of this analysis was to influence configuration selection and design by identifying single-point failures which could result in a catastrophic condition. For the analysis, the candidate configurations were divided into five functional areas. These areas included (1) sensor inputs, (2) pilot controller inputs, (3) primary and secondary actuators, (4) flight crew displays, and (5) computational schemes. The analysis results as related to each functional area are summarized in the following paragraphs.

2.15.2 SENSOR INPUTS - Considered during the analysis were rate sensors, accelerometers, and dynamic pressure sensors. A potentially catastrophic single-point-failure associated with the rate sensor and accelerometer packages was identified; a loose or broken mounting provision would cause multiple erroneous and/or erratic outputs from the affected sensor package. These signals would generate uncommanded pitch, roll, or yaw excursions, and depending upon the flight conditions and characteristics of the inputs, possible loss of aircraft control could occur. To reduce the criticality of these single-point-failures, a safety switch could be added to the base of each gyro and accelerometer package to detect any condition where the package becomes loose or disconnected from the airframe. The switch would activate logic within the DFCS which will disregard the false or spurious signals and select alternate control laws. This results in the elimination of all single-point critical and catastrophic conditions associated with sensor component mounting.

The prime function of the dynamic pressure sensor packages (dual units in parallel) is to provide inputs for automatic gain scheduling. There are several single-points-of-failure which could cause the sensor inputs to be erroneous and result in incorrect gain scheduling. Examples include a cracked, broken, or plugged pitot or static line, or a cracked bellows on one sensor unit. The criticality of these failures would be largely dependent upon flight conditions at the time of the failure and pilot awareness of erroneous scheduling. To resolve this problem, a data reasonableness test will be used to detect the failure. The pilot will then be alerted to the automatic gain scheduling problem and have the capability to select the gains manually.

2.15.3 PILOT CONTROLLER INPUTS - The primary flight controllers include the side stick controller, rudder pedal assembly, and throttle controller. These provide for the control of pitch, roll, yaw, direct lift, direct side force, engine thrust, and the selection of certain flight modes. The analysis of these controllers identified a potential single-point-failure associated with the rudder pedal assembly. If the pedal support is jammed or disconnected, or the pedal transducer attach point or feel cylinder is disconnected, the yaw command inputs would be fixed. Continued aircraft control would then be dependent upon flight conditions and rudder surface deflection at the time of the failure.

2.15.4 PRIMARY AND SECONDARY ACTUATORS - All longitudinal, lateral, and directional primary and secondary actuators were considered during the analysis. Several failures were identified which would result in the complete loss of actuator function, i.e., loss of control of the affected surface. These failures were categorized either as total actuator motion stopped, e.g., piston seizure or jam, or loss of actuator output, e.g., summing shaft or rod end broken. In the case of the stabilator and rudder primary and secondary actuators and the canard actuators, some of these failures could result in catastrophic conditions. Reduction in the criticality of the canard actuator failures could be accomplished in one of two ways:

(a) The actuator stroke might be mechanically or hydraulically limited to produce ±15° canard surface travel. This results in elimination of one catastrophic condition. The actuator rod end failure remains a potential catastrophic situation.

(b) Mechanical stops might be incorporated to physically limit canard surface motion to ±15°. This eliminates all identified catastrophic conditions associated with the canard actuator.

2.15.5 FLIGHT CREW DISPLAYS - The flight crew displays including the HUD, MFD's, and CDC readouts were reviewed to determine the criticality of a complete loss of function on each display. No significant single-point-failures were identified.

2.15.6 COMPUTATIONAL SCHEMES - The primary source of angle-of-attack (α) and sideslip angle (β) signals for the Digital FCS control laws will be the α and β estimators. The estimators will be mechanized in each flight control computer and depend upon data inputs from other aircraft sources. Since these estimators are redundant, the only single failures which could cause erroneous signals from all α and β estimators would be failures associated with these data inputs, e.g., velocity, Mach number, and dynamic pressure. It has been determined that α and β input signals are not required for a return and land capability. However, allowing incorrect α and/or β inputs into the control laws would affect performance, and control problems could develop in some instances. The most critical area affected would be the departure prevention logic. If the pilot is relying on this logic and the function is in error, inadvertent aircraft departure could occur. To correct this situation, the estimator schemes will employ a failure detection technique which uses α and β probe inputs. The probe inputs will be electrically dual from each of the two α sensors and the single β sensor. When the detection scheme declares the estimators to be in error, the departure prevention logic will be disabled and the pilot alerted.

2.15.7 CONCLUSIONS - The conclusions from the single-point-failure analysis are as follows:

- The single-point-failures identified during the analysis were common to all candidate Digital FCS configurations.
- A criticality ranking by aircraft axis shows the longitudinal axis to be the most critical, and is followed by the directional axis. No catastrophic single-point-failures were identified in the lateral axis.

2.16 SAFETY ANALYSIS

2.16.1 GENERAL - A safety analysis, which included a Failure-Mode-and-Effect Analysis (FMEA), has been conducted on the three sound candidate Digital FCS configurations to provide a risk comparison of the configurations and to identify the safety-critical components. These components were those where single-point-failures would result in Class IV Catastrophic or Class III Critical Hazards. These hazards are defined as follows:

- Class IV Catastrophic - Hazards that will cause death or loss of the aircraft and for which there is no time for corrective action.
- Class III Critical - Hazards that will cause serious personnel injury or major system damage, or will require immediate corrective action to prevent death or loss of the aircraft.

2.16.2 FMEA RESULTS - For the potential single-point-failure hazards which were identified, the following were determined:

- LRU or WRA involved,
- Analog or digital FCS,
- Failure mode,
- Cause,
- Failure effect,
- Hazard classification, and
- Probability of occurrence.

Potential Class IV hazards, assuming provisions discussed in Section 2.15 were implemented, are summarized in Table 22. A comparison is also made to the PACT configuration.

Table 22
Failure-Mode-and-Effect Analysis Summary of Results

Configuration	Class IV Hazards (n)	Class III or IV Hazards(1) (m)	Total $P_{F_{IV}}$ x $(10)^{-7}$
Digital FCS (Conf A, B, or C) with Analog Backup	3	2	4.18
Digital FCS (Conf A, B, or C) Without Analog Backup	3	2	3.08
SFCS with Canards (PACT Configuration)	5	4	11.08

$P_{F_{IV}}$ = Probability of a Class IV Hazard

$$P_{F_{IV}} = \sum_{i=1}^{n} (P_{F_{IV}})_i + 0.1 \sum_{j=1}^{m} (P_{F_{III}} \text{ or } P_{F_{IV}})_j$$

n = Number of Possible Class IV Hazards
m = Number of Possible Class III or IV Hazards
(1) = Class IV Only at high q and/or Landing or Takeoff

2.16.3 ADDITIONAL SAFETY STUDIES - Additional safety studies were conducted of specific portions of the Digital FCS configurations which could be critical to ground and/or flight safety. These were:

- Outer loop inputs,
- Normal Mode select circuitry, and
- Mode-select and display interface.

2.16.3.1 Outer Loop Inputs - Table 23 contains a list of the outer loop inputs which were considered during this study and the respective functions which utilize these inputs. An assessment of the safety impact related to each of these functions is summarized below:

Table 23
Digital FCS Outer Loop Inputs

Outer Loop Input	Function			Used for
	Gain Scheduling	α and β Estimation	Gravity Correction	
Velocity (V)	X	X	X	Mach Hold
Altitude (h)				Altitude Hold and Energy Management
Dynamic Pressure $\bar{q}$	X			Normal Mode
Altitude Rate ($\dot{h}$)				Altitude Hold and Energy Management
Mach Number (M)	X	X		Mach Hold and Energy Management
Pitch Angle (θ)			X	Attitude Hold, ACL, Energy Management
Bank Angle (ϕ)			X	Attitude Hold, ACL
Mass (m)		X		
Density (ρ)		X		
Angle-of-Attack (α)	X	X		
Sideslip Angle (β)		X		
Data Link-Control Commands				ACL
ILS-Control Commands				Automatic ILS

Note: X - Indicates Outer Loop Input Required

- Gain Scheduling - Dynamic pressure ($\bar{q}$), Velocity (V), and Mach number (M) signals from the $\bar{q}$ sensors are used extensively in the various control laws as gain scheduling parameters. Two $\bar{q}$ sensors receive pitot and static pressure inputs from the pitot-static system. Each sensor package contains a bellows which measures the difference of these two pressures and mechanically drives the wipers of two potentiometers. This results in two electrical output signals from each sensor package which are used for automatic gain scheduling. A failure of one of these four electrical outputs can be readily detected using comparison techniques and the failed signal removed. Failures upstream of the $\bar{q}$ sensors; in the pitot-static system, could cause erroneous electrical outputs from all four potentiometers. It is planned that a velocity signal from an independent source such as the INS will be utilized for comparison with the velocity output of the $\bar{q}$ sensors to enable detection of this type of failure. A significant deviation among these signals could then be employed to automatically select a discrete safe gain and/or notify the pilot.

- o <u>α and β Estimation</u> - A failure or malfunction of one or more of the sensing elements associated with velocity (V), Mach number (M), mass (m), and density (ρ) would cause erroneous α and β estimations. The safety criticality of this condition and the method of control have been previously discussed in Section 2.15.6.

- o <u>Gravity Correction</u> - Failure or malfunctions causing the loss of the gravity correction feedback term are not considered to be safety critical.

- o <u>Pilot-Relief Modes</u> - The capability to immediately revert to the Normal Mode will effectively control the criticality of failures causing the loss of any or all pilot-relief modes.

2.16.3.2 <u>Normal Mode-Select Circuitry</u> - Due to the wide range of capabilities provided by the Normal Mode including a return and land capability, the mode-select circuitry must provide a high probability that the mode will be engaged when commanded by the pilot. In order to investigate the options available, a study was performed to define and evaluate several mode-select configurations. To provide high reliability, three means of selection of the Normal Mode, with switches on the side stick controller (SSC), on the CDC, and an additional Normal Mode switch, was chosen as the desirable configuration as shown in Figure 59.

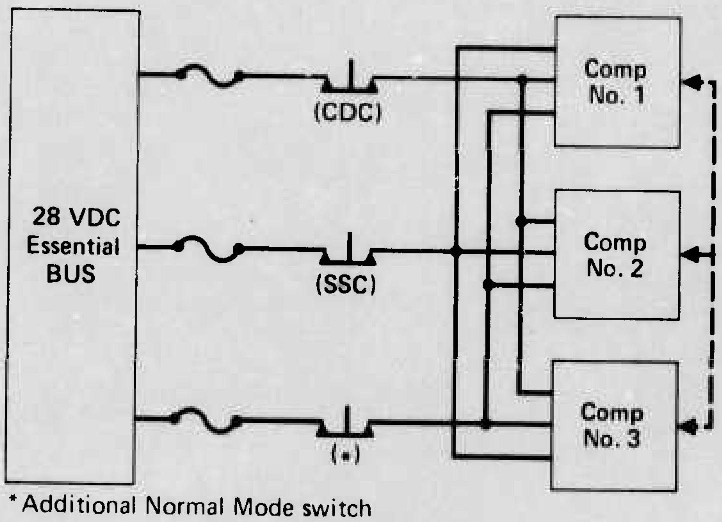


Figure 59
Normal Mode Select Configuration

2.16.3.3 <u>Mode-Select and Display Interface</u> - A study was performed on the equipment and associated interfacing functions required for the Digital FCS mode selection, display selection, and display readout capabilities. The purpose of this analysis was to identify safety considerations for use in the interface design. The safety considerations identified by this study include:

- o All pilot-assist mode select signals from the CDC, the throttle levers, or the SSC should be separated into two functional paths. One path should address the display and/or flight management computer, and the other path should address the flight control computers.

- Failure and fault information which is critical to flight, emergency procedures, and FCS operational status, if requested by the pilot, should have display priority.

- Failure and fault reset capabilities should receive careful attention.

2.16.4 CONCLUSIONS - The conclusions of the safety analysis are as follows:

- The FMEA identified the safety-critical components.

- All three Digital FCS configurations are identical with respect to the number and probability of occurrence of Class IV hazards.

- Utilizing an analog backup during the initial portion of the flight test program would not significantly modify the probability of a catastrophic failure.

- With regard to Class IV hazards, the Digital FCS configurations demonstrated a significant improvement over the PACT configuration.

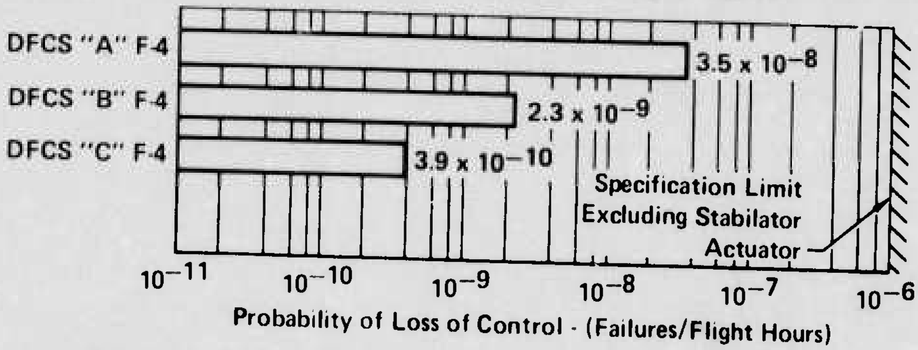
- The criticality of all failures associated with the outer loop inputs has been reduced or controlled to an acceptable level of safety.

- The Normal Mode select configuration chosen for design provides a high probability that the mode will be engaged when commanded by the pilot.

- Implementation of the safety considerations provided for the design of the mode-select and display interface should result in the elimination of safety-critical failures.

2.17 RELIABILITY ANALYSIS

2.17.1 GENERAL - The three sound candidate configurations were analyzed for the probability of loss of control from cumulative failures in the DFCS control paths for comparison with the Statement of Work reliability goal of no more than two catastrophic failures per 10^6 flight hours (displays were excluded from the analysis). The results obtained are presented in Figure 60. The probabilities shown are for the redundant command paths through and including the redundant portions of the secondary actuator. As indicated on Figure 60, the stabilator actuator and associated linkages, common to all the configurations, were excluded from the chart and the specification was correspondingly reduced to one failure per 10^6 flight hours.



Notes: (1) DFCS configurations include expected coverage
(2) Stabilator actuator failure rate is 1.0×10^{-6} failures per flight hour as derived from AFM 66-1 data and is not included in the probabilities shown
(3) Excludes electrical and hydraulic power supplies

Figure 60
Reliability Comparison

An expected coverage was applied to each component of Configuration "A" and Configuration "B". The expected coverage reflects the fact that currently-planned in-line monitoring will not be able to detect all failures of the monitored equipment. The expected coverages used in this analysis are presented in Table 24.

Table 24
Expected Coverages

Component	Expected Coverage (Percent)
Pilot Input Sensors	99.9
Rate Gyros	74.0
Normal Accelerometers	97.0
1/2 DIF (Input)	99.5
Computer–Computer Interface	99.5
Digital Computer	99.5
1/2 DIF (Output)	99.5
Power Supply-Servo Amp	99.9
Secondary Actuator Element	99.9

All three axes were considered in setting up the original reliability equations from which the data presented in Figure 60 were derived. However, a basic ground rule was that the F-4 could be landed on a runway with pitch control and either roll or yaw control. The "or" provision with respect to roll and yaw places these two axes in parallel making the combined total for the two axes so small that the roll-yaw failure probabilities drop out in the round-off when roll-yaw is combined with the failure probabilities for the pitch axis. As a practical matter, therefore, the values derived are those for the critical pitch axis.

2.17.2 CONCLUSIONS - Any of the three sound candidate configurations can provide adequate reliability to meet the Statement of Work requirement if the expected coverage is obtained. Reliability degradation which can be expected with reduced coverage is presented in Section 2.12.

2.18 MAINTAINABILITY ANALYSIS

2.18.1 GENERAL - The three sound candidate DFCS configurations were analyzed to determine the estimated maintainability parameters necessary to support the Digital Flight Control System (displays were excluded from the analysis). The objective of this analysis was to provide a realistic basis for determining the relative support resources and logistics costs for each configuration.

The repair times for the installed system on the aircraft, and the LRU's in the shop, are based generally on the maintenance concept indicated in Figure 61 "Digital FCS Maintenance Flow". This concept is predicated on a design which provides for a built-in test capability and minimizes the need for any external organizational level AGE except for electrical and hydraulic power carts. Detected faults will be isolated to the faulty LRU which is then removed and replaced with a serviceable spare. Built-in test is also utilized to verify the system repair.

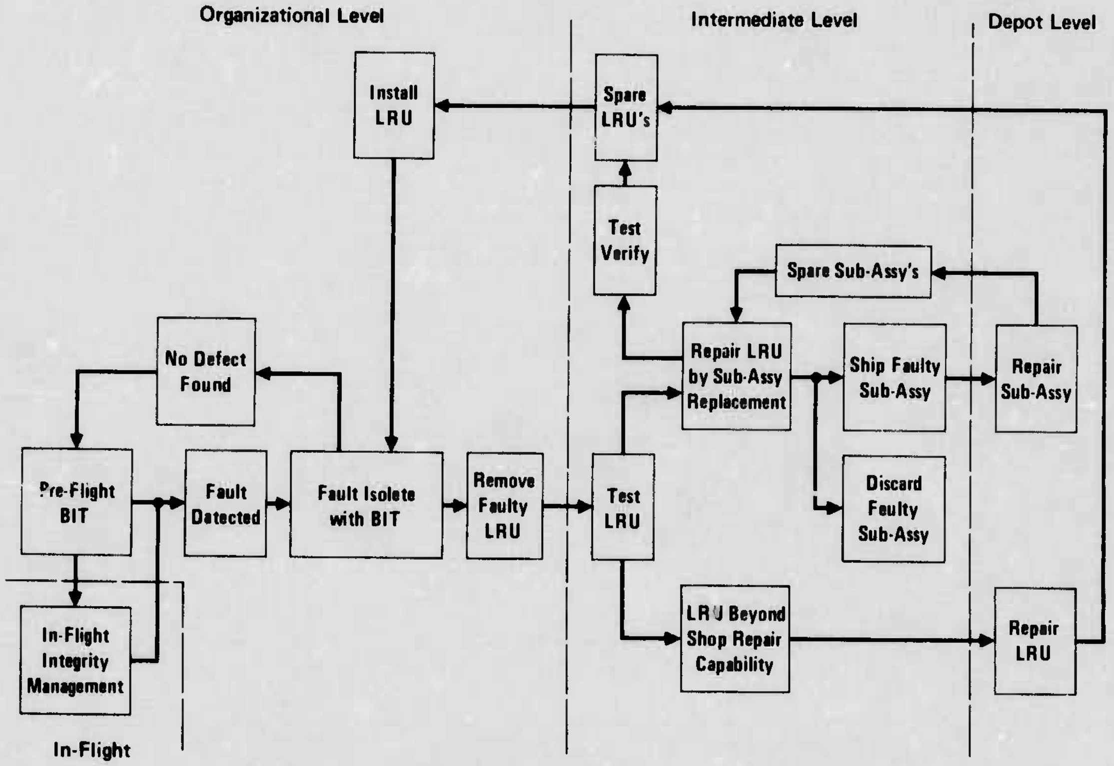


Figure 61
Digital FSC Maintenance Flow

The intermediate level repair times are predicated on a packaging design which permits direct rapid access to modular plug-in subassemblies, and includes sufficient test points brought out to external test connectors capable of interfacing with automatic computer controlled test stations capable of effecting isolation to a faulty plug-in module subassembly. The repair times and the maintenance action rates for comparable LRU's having similar capabilities were obtained. These parameters were used to modify the appropriate reliability and maintainability quantities which were applicable to each Digital FCS LRU.

2.18.2 MAINTENANCE TASK ANALYSES

(a) Unscheduled Maintenance - Maintenance Task Analyses were performed for each of the three sound candidate DFCS configurations. Unscheduled Maintenance Manhours per Operate Hour (MMH/OH) was calculated for each LRU in each configuration to obtain the totals for each configuration. The Maintenance Action Rates (μ) and Mean Maintenance Manhours to Repair (MMTR) were calculated for Organizational level (on aircraft) and Intermediate level (shop) maintenance. Table 25 summarizes the maintenance manhours and Table 26 summarizes the maintainability parameters for each configuration.

Table 25
Maintenance Manhour Comparison Summary

	Organizational Level MMH/OH	Intermediate Level MMH/OH	Total MMH/OH	Total(1) MMH/FH
Configuration A	0.056	0.032	0.087	0.262
Configuration B	0.061	0.038	0.099	0.298
Configuration C	0.063	0.040	0.103	0.309

(1) Assumes 3 operating hours per flight hour.

Table 26
Maintenance Parameter Summary(4)

	Organizational Level				Intermediate Level		
	Quantity of LRU's	μ_{OH}(1) x 10^6	MTBMA(2)	MMTR(3)	μ_{OH}(1) x 10^6	MTBMA(2)	MMTR(3)
Configuration A	29	16,700	59.6	0.649	13,600	73.6	2.33
Configuration B	30	19,200	52.1	0.651	16,000	62.6	2.37
Configuration C	31	20,500	48.7	0.620	17,200	58.0	2.32

Notes: (1) Maintenance actions per million operate hours.
(2) Mean time between maintenance actions.
(3) Mean manhours to repair
(4) Does not include aircraft peculiar maintenance tasks

(b) Scheduled Maintenance - DFCS batteries will require inspection and servicing on a 60-day basis.

2.18.3 AVAILABILITY - Availability is a measure of the degree to which an item is in the operable and committable state at the start of the mission, when the mission is called for at an unknown (random) point in time. A comparison of the DFCS configurations indicating the relative availability, maintenance manhours per operate hour, and time to repair is listed in Table 27.

Table 27
Flight Line Maintenance Comparison Summary

Configuration	Mean Corrective Down Time (MCDT) (Elapsed Hours)(3)	Mean Maintenance Manhours to Repair (MMTR)(3)	Maintenance Manhours per Operate Hour (MMH/OH)	Availability(1)
F-4 DFCS 'A' (3-3-3)(2)	1.76	2.20	0.021	0.98
F-4 DFCS 'B' (4-3-4)(2)	1.84	2.23	0.025	0.97
F-4 DFCS 'C' (4-4-4)(2)	1.76	2.15	0.027	0.97

Notes:

(1) Availability = $\frac{\text{Mean Time Between Maintenance Actions (MTBMA)}}{\text{MTBMA + MCDT}}$

(2) Excludes Canard Actuators, Integrated Torque Boosters, and Displays

(3) Includes Aircraft Peculiar Maintenance Tasks

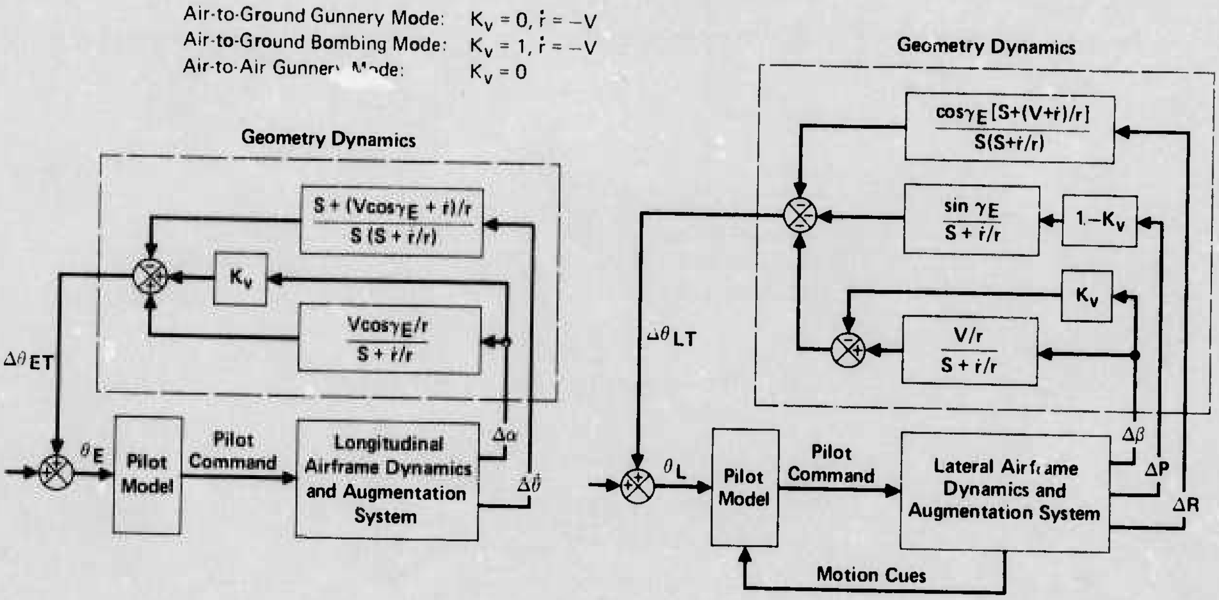
2.18.4 CONCLUSIONS

- Any of the three sound candidate configurations are expected to produce very significant reductions in maintenance manhours per flight hour compared to mechanical control systems,
- Configuration A (triplex) would require less maintenance manhours per flight hour than either of the other configurations, and
- The availability of all three configurations is approximately 97%.

2.19 EFFECTIVENESS ANALYSIS

2.19.1 INTRODUCTION - Analyses were performed to ascertain the effectiveness of the DFCS multimode control laws for combat mission segments defined by the mission scenario. The analyses were performed using data collected from an all-digital simulation performed in the course of the DFCS control law synthesis and data collected from the man-in-the-loop simulations. The effectiveness analyses employed the effectiveness evaluation criteria discussed in Section 2.3.2.

2.19.2 ALL-DIGITAL EFFECTIVENESS ANALYSES - All-digital effectiveness analyses were utilized in the design of the weapon delivery mode control laws. The all-digital effectiveness analyses employed theoretical tracking models from Reference (25) consisting of linearized aircraft and control system dynamics, tracking geometry relations and a constant gain pilot model. The tracking models are depicted in Figure 62. The pilot gains used in the simulations were the gains which generated the best responses and which corresponded closely to the gains providing the best system damping.



Elevation

Traverse

Figure 62
Theoretical Tracking Effectiveness Models

Representative time histories of the normalized tracking error responses obtained using the all-digital simulation tracking models are illustrated in Figure 63 for air-to-ground gunnery with the roll axis stabilized about the gun line, and for air-to-ground bombing with the roll axis stabilized about the velocity

Reference: 25. Berger, J. B., et al, "Flight Control Requirements for Weapon Delivery, Interim Report for Period June 1973 through May 1974", Technical Report AFFDL-TR-74-119, October 1974.

vector. The figure shows the capability of the Direct Lift, Lateral Translation and Flat Turn functions for nulling small tracking errors as compared to using only stick inputs. A summary of these data are presented in Table 28.

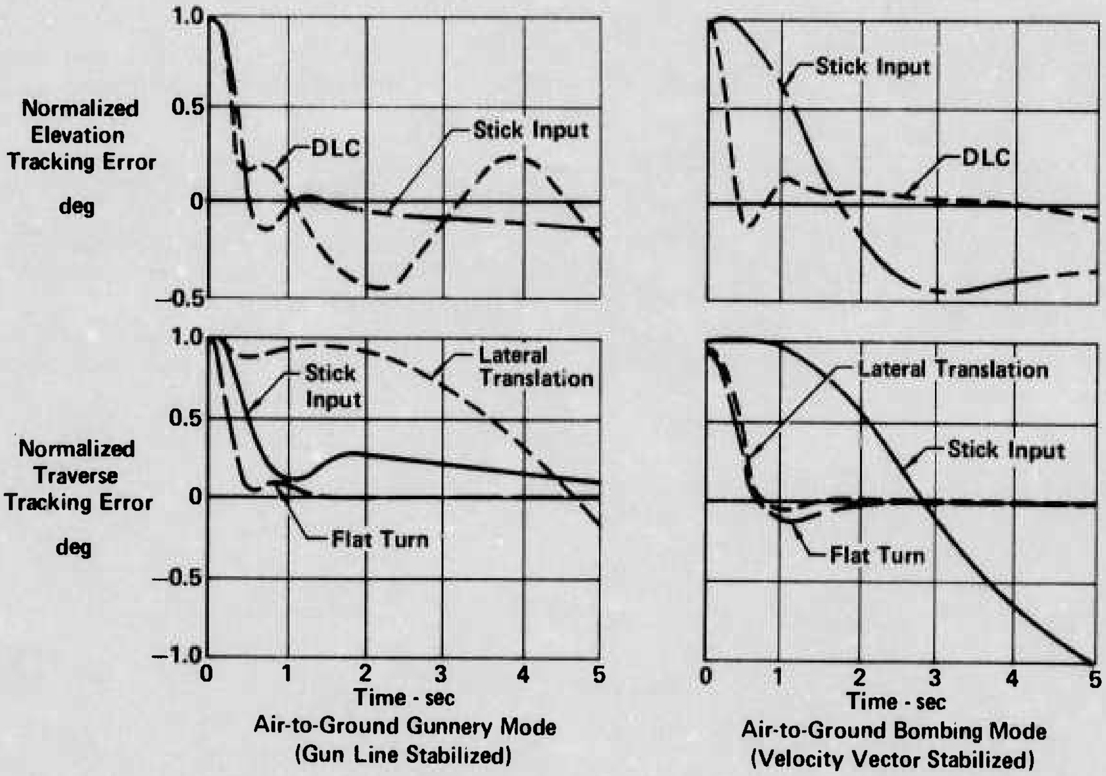


Figure 63
Normalized Tracking Error Responses

Table 28
Capability to Null Small Tracking Errors

	Air-to-Ground Bombing (Velocity Vector Stabilized)	Air-to-Ground Gunnery (Gun Line Stabilized)
DLC Superior to Longitudinal Stick	Yes	No
Flat Turn Superior to Lateral Stick	Yes	Yes
Lateral Translation Superior to Lateral Stick	Yes	No

2.19.3 MAN-IN-THE-LOOP SIMULATION EFFECTIVENESS RESULTS - Two man-in-the-loop simulation programs were conducted in which customer pilots participated and effectiveness data were accumulated. The Control Law Simulation took place between 30 September 1974 and 11 October 1974 on the SFCS Flight Simulator with five pilots participating. The objectives were to evaluate and refine the control law design, based on effectiveness and handling qualities criteria, with conventional cockpit displays. The primary cockpit controller consisted of a base-pivot SSC mounted at the right armrest of the pilot's seat. The second simulation, the Integrated Control Law and Display Simulation, took place between 9 December 1974 and 17 January 1975 on the MACS III air combat simulator with seven pilots participating. The objectives were to further evaluate and refine the control laws and advanced cockpit displays, to increase weapon delivery effectiveness and reduce pilot workload in the performance of a complete mission scenario. In this simulation the base-pivot SSC was replaced with a laboratory model palm-pivot SSC.

During both simulations, the weapon delivery mission segments were flown using the DFCS multimodes and the DigiPACT mode, for the purpose of comparing the DFCS multimode effectiveness against the effectiveness of a general purpose fighter control law. The primary data reduction method was statistical. The equations which form the basis for this data reduction are presented in Table 29. After each simulation, the tracking data were reduced by statistically combining tracking results from all the pilots participating in that simulation. For the purposes of data reduction, each pilot's results were weighted equally, and no attempt was made to modify the results based on experience or performance. In addition, a figure of merit data reduction method was used to examine the results.

Table 29
Basic Statistical Analysis Equations

- **Mean** $(\bar{X}(k))$

$$\bar{X}(k) = \frac{1}{k} \sum_{n=1}^{k} x_n$$

- **Variance** $(E[X - \bar{X}]^2)$

$$E[X - \bar{X}]^2 = \frac{1}{k} \sum_{n=1}^{k} X_n^2 - \left(\frac{1}{k} \sum_{n=1}^{k} X_n\right)^2 = \frac{1}{k} \sum_{n=1}^{k} X_n^2 - \bar{X}^2(k)$$

- **Standard Deviation** $(E[X - \bar{X}])$

$$E[X - \bar{X}] = \sqrt{\text{Variance}}$$

x is the variable
n is the nth sample
k is current total number of samples

2.19.3.1 Control Law Simulation Effectiveness Results - The tracking response data of Figure 64 are representative of the raw data collected during the man-in-the-loop simulations. Representative statistical effectiveness data from the Control Law Simulation are presented in Figures 65 and 66. Each figure shows the statistical mean of the tracking error with the spread of the data represented by the ± 1 standard deviation marks on either side of the mean value. For comparison purposes the statistical data has been normalized to the maximum mean +1 standard deviation. Interpretation of these data can be based on the standard deviation which is an indication of the variance of the tracking response motion. The mean error may also be of some significance; however, experience has shown that pilots often track a target point offset by a bias distance proportional to the range to the actual target. This bias will cloud any conclusions which can be drawn from the mean tracking error.

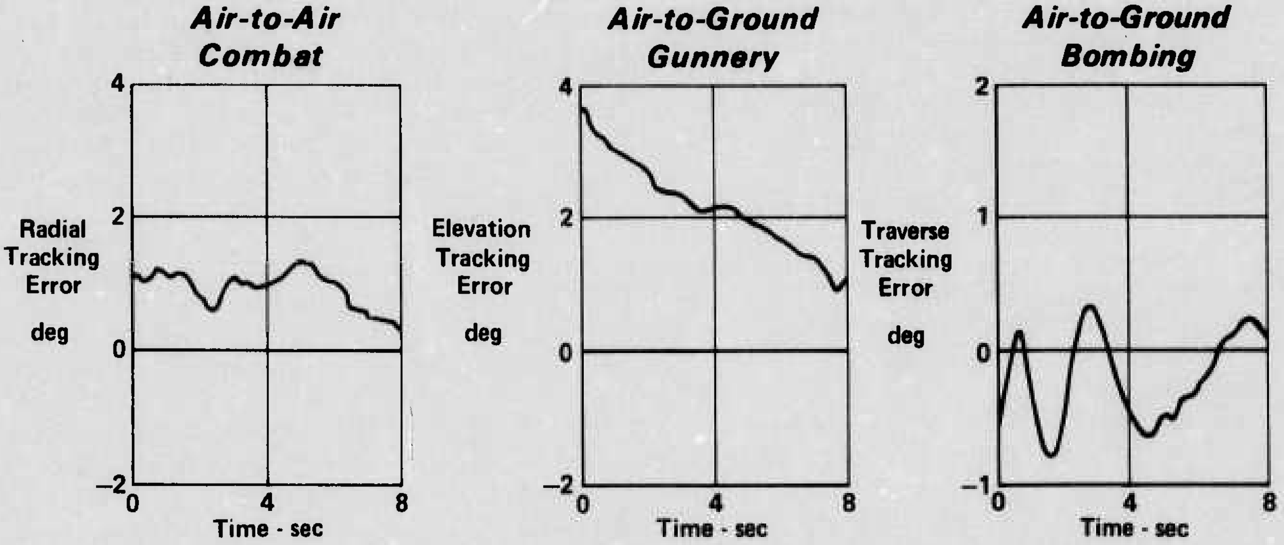


Figure 64
Man-in-Loop Simulation
Representative Tracking Response Data

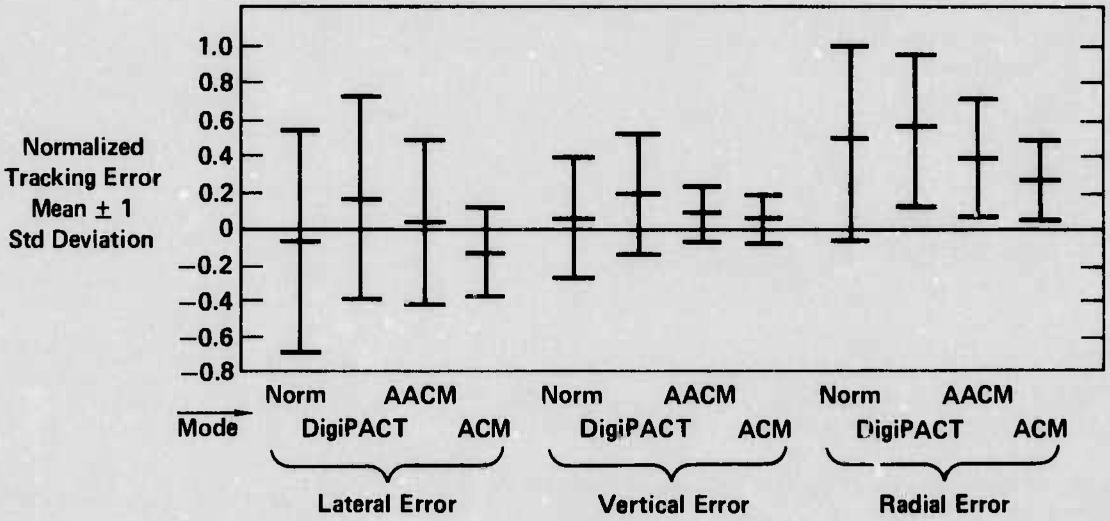


Figure 65
Control Law Simulation
Representative Air-to-Air Combat Effectiveness Data

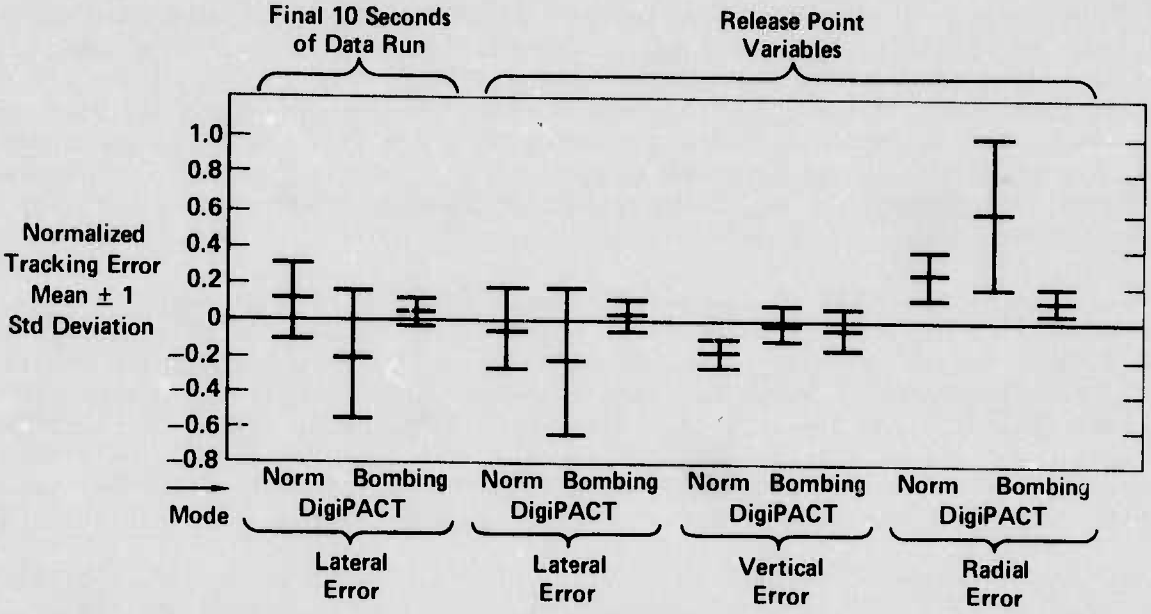


Figure 66
Control Law Simulation
Representative Air-to-Ground Bombing Effectiveness Data

Two preliminary air-to-air combat modes investigated during the Control Law Simulation were the ACM and the AACM. The air-to-air tracking results presented in Figure 65 show that the ACM was superior to the AACM, and the AACM was therefore dropped from further evaluation. Both the Normal Mode and DigiPACT Mode were included in these data to form a baseline for data comparisons. The air-to-air tracking data shown were taken during an eight second period of a tracking maneuver in which the target maintained a 3g turn. The superiority of the ACM in the tracking role resulted from providing improved pitch control at high angles-of-attack and improved roll characteristics.

Figure 66 presents representative bombing effectiveness data results for the Normal, DigiPACT and Air-to-Ground Bombing Modes. The lateral tracking error was analyzed for 10 seconds prior to bomb release and at the bomb release point, while the other errors were analyzed at the bomb release point only. The data shows the Air-to-Ground Bombing Mode superior to the other modes in tracking to the target and capturing the desired release point conditions. Bombing effectiveness results show that most of the improvement with the Bombing Mode was in the lateral axis where the elimination of the pendulum effect and the ability to roll around a stabilized velocity vector produced superior lateral tracking. The flat turning capability was useful in eliminating small tracking errors. Lateral translation was used to advantage to offset crosswinds on the bomb runs. No Air-to-Ground Gunnery Mode effectiveness data are presented for the Control Law Simulation because an error, which influenced the effectiveness data results, was discovered in the simulation of the Air-to-Ground Gunnery Mode subsequent to the end of the simulation.

Pilot comments concerning the Control Law Simulation indicated that the mount and armrest adjustability of the base-pivot SSC was inadequate. As a result, in the interim period between the Control Law Simulation and the Integrated Control Law and Display Simulation, MCAIR pilots evaluated the base-pivot SSC with improved adjustment capability against a laboratory model palm-pivot SSC. MCAIR pilots found that they preferred the laboratory model palm-pivot SSC. Therefore, this SSC was used in the Integrated Control Law and Display Simulation with the forces adjusted to MCAIR pilots' preferences.

2.19.3.2 Integrated Control Law and Display Simulation Effectiveness Results - Air-to-air tracking was performed in the Integrated Control Law and Display Simulation with a fixed reticle display alone and with a fixed reticle display and additional pertinent information on the HUD. Air-to-ground segments were flown with these two types of fixed reticle displays and also with a computed or dynamic reticle display. No significant difference was noted in the relative tracking results as a function of the display used. Therefore, tracking data for the Integrated Control Law and Display Simulation can be represented by the fixed reticle display results alone.

Representative statistical results for the fixed reticle display are shown in Figures 67 and 68. The limited time available for the Integrated Control Law and Display Simulation permitted comparison of the weapon delivery modes to the DigiPACT Mode only. The data presented in Figure 67 for the air-to-air combat segment show the ACM to be superior compared to the DigiPACT Mode. Results of the air-to-ground guns segment showed the Air-to-Ground Gunnery Mode superior to the DigiPACT Mode in tracking effectiveness. Features which contributed to the superiority of the Air-to-Ground Gunnery Mode included flat turn capability, roll about the gun line axis, and pitch rate control for small pitch inputs. Bombing results are not included in these data as the results were not found to be significantly different from the Control Law Simulation.

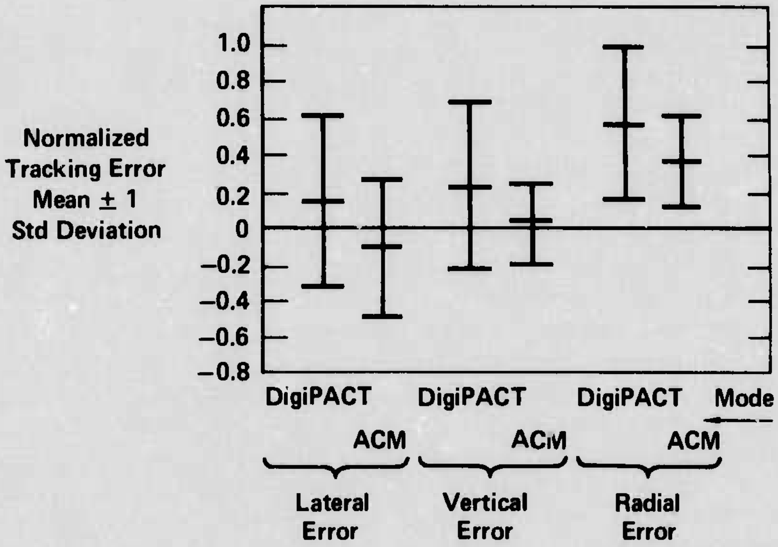


Figure 67
Integrated Control Law and Display Simulation
Representative Air-to-Air Combat Effectiveness Data

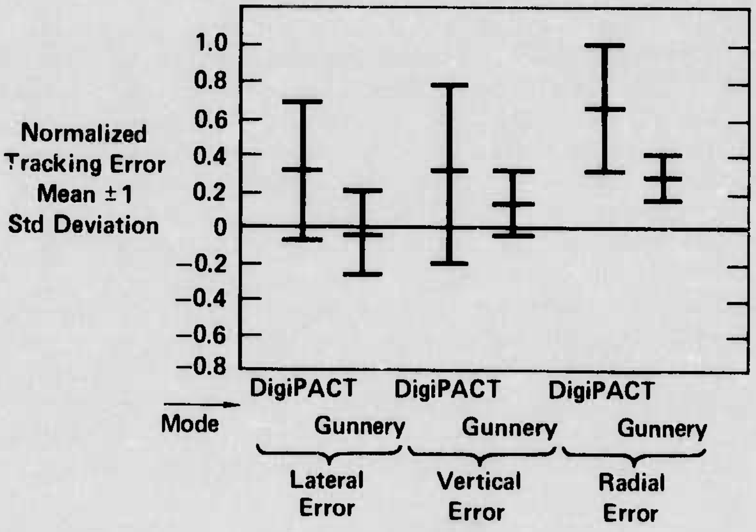
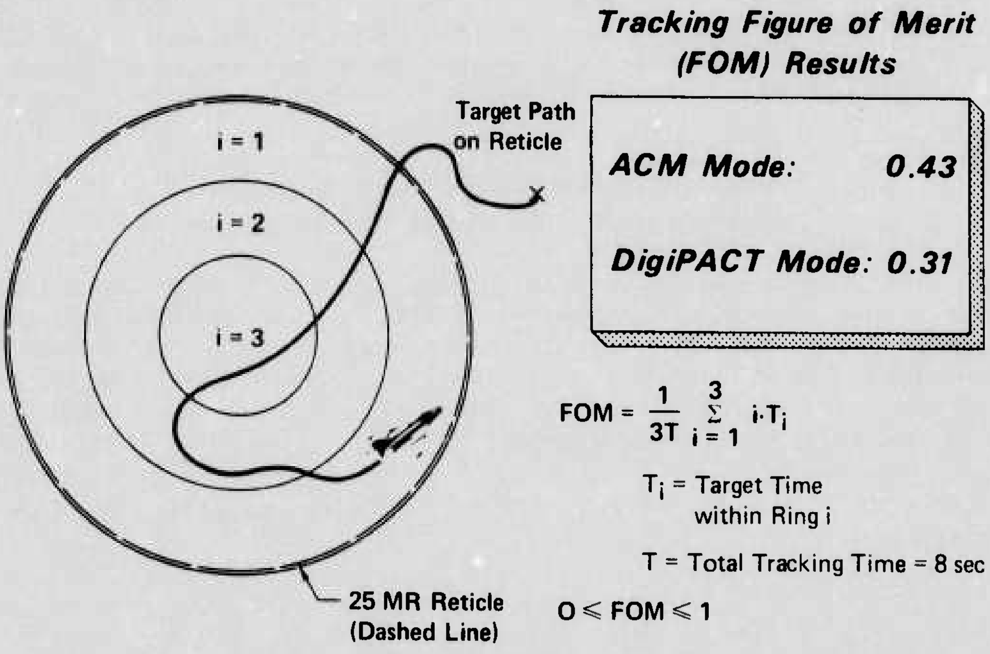


Figure 68
Integrated Control Law and Display Simulation
Representative Air-to-Ground Gunnery Effectiveness Data

Several additional types of data reduction were employed to obtain some additional information on the data trends of the Integrated Control Law and Display Simulation. The results of a Figure of Merit method are shown in Figure 69 for the air-to-air combat segment. Superiority of the ACM is apparent from these data which quantify the visual observations made by pilots and simulation observers.



$$\mathrm{FOM} = \frac{1}{3T} \sum_{i=1}^{3} i \cdot T_i$$

T_i = Target Time within Ring i

T = Total Tracking Time = 8 sec

$0 \leq \mathrm{FOM} \leq 1$

Figure 69
Integrated Control Law and Display Simulation
Representative Air-to-Air Combat Effectiveness Data

The data presented in Figure 70 is a comparison of effectiveness data from the Integrated Control Law and Display Simulation between pilots who had not previously participated in the simulated weapon delivery and pilot who had previously participated in the Control Law Simulation. Tracking results for the air-to-air combat segment show that the pilots with the previous experience achieved approximately equal performance with the ACM and DigiPACT Modes while the other pilots achieved better performance with the ACM. This comparison indicates that with sufficient experience, a pilot who is well rehearsed in a particular air-to-air tracking profile can learn to perform well on the simulator with either the ACM or DigiPACT Mode. On the other hand, a pilot without the previous experience or one who is performing a more realistically unfamiliar profile can achieve better results with the ACM than with the DigiPACT Mode. Additional supporting evidence of this result is apparent in the air combat effectiveness comparison in Figure 71 where overall tracking effectiveness with all four control modes was improved and the relative differences among modes were reduced for the second data taking session (Friday) as compared to the initial data taking session (Tuesday) of the Control Law Simulation.

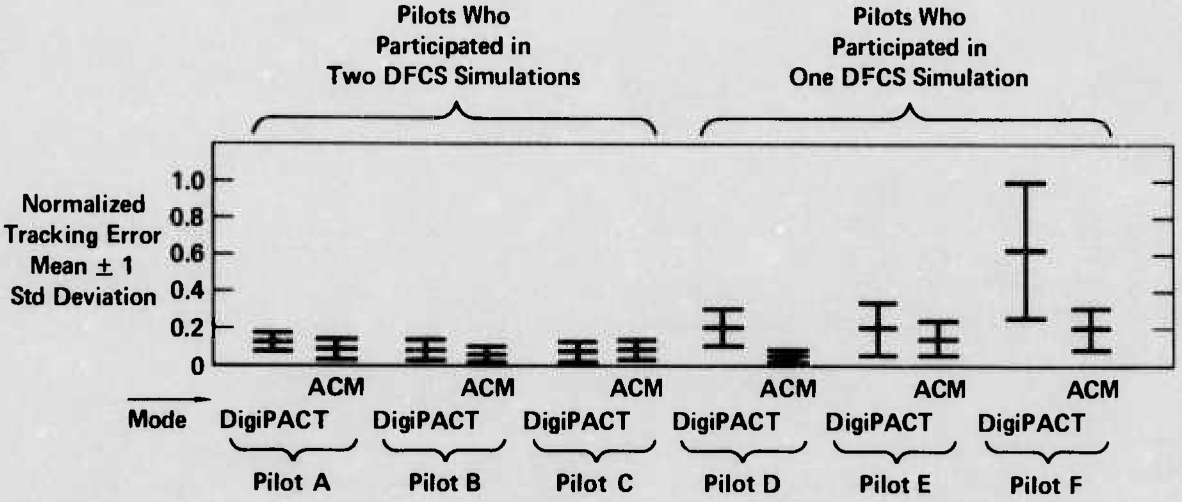


Figure 70
Integrated Control Law and Display Simulation
Comparison of Air-to-Air Combat Effectiveness Data

On the final day of the Integrated Control Law and Display Simulation, three of the customer pilots evaluated the base-pivot SSC, with improved adjustability, by performing air-to-air tracking. Statistical tracking data were not recorded for these evaluations, but the tracking was visually observed to be significantly improved with the base-pivot SSC, and the pilots stated their preference for the base-pivot SSC in the final debriefing session.

Further work on the SSC is required to determine the most desirable stick characteristics.

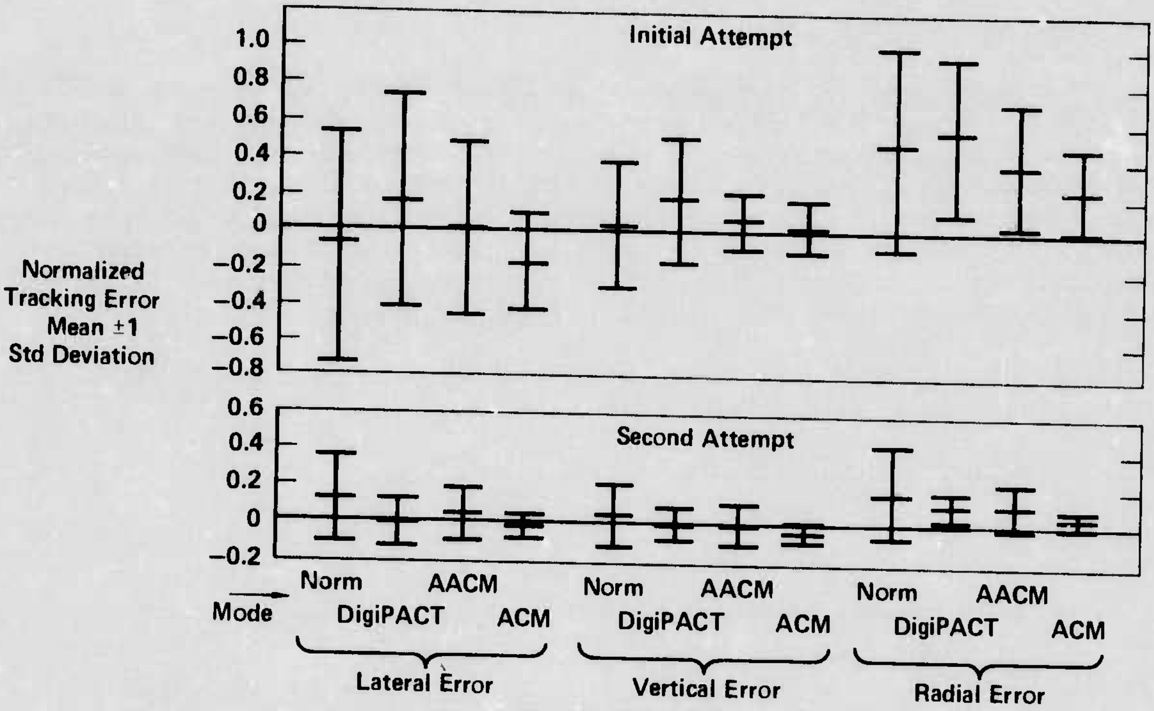


Figure 71
Control Law Simulation
Comparison of Air-to-Air Combat Effectiveness Data

2.19.4 CONCLUSION - Increased tracking effectiveness using the multimodes was found to exist in both the DFCS man-in-the-loop simulations. The trend of the statistical data shows that the multimode control laws produce better tracking results. The figure of merit data analyses produced essentially the same results as visually observed by the pilots, indicating that the multimode control laws were more effective. The combined effects of pilot experience with the ACM and the DigiPACT Mode, and experience in tracking a target aircraft performing duplicate evasive maneuvers in each simulation show that the pilots can compensate for differences in the control laws. On the other hand, with less previous experience, and confronted with more realistically unfamiliar target flight profiles, the pilots were more effective with the ACM multimode.

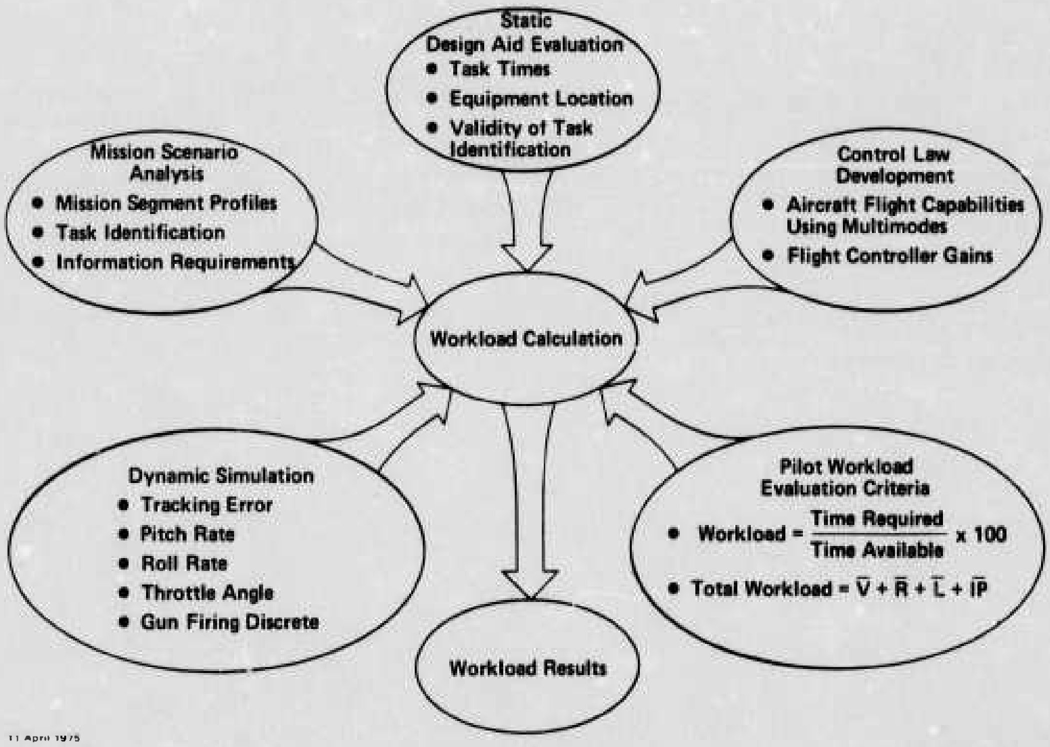
2.20 WORKLOAD ANALYSIS

2.20.1 INTRODUCTION - An analysis has been performed in which pilot workload was estimated and measured in both static and dynamic (man-in-the-loop) simulations. The purpose of the analysis was to show the effect of the DFCS configuration on pilot workload throughout all phases of the aircraft mission. It is intended that the workload values be used as comparisons of pilot workload rather than absolute values, e.g., comparisons of pilot workload differences between mission segments or comparisons of different crew station configurations. The analytical methods used and results obtained are presented in the following paragraphs.

2.20.2 ANALYTICAL METHODS - The workload analysis utilized inputs from a variety of DFCS analyses and simulations. These included:

- Mission Scenario Analysis (see Section 2.2),
- Static Design Aid Evaluation (see Section 3.2),
- Control Law Development (see Section 2.4),
- Dynamic (man-in-the-loop) Simualtions (see Section 3.3), and
- Workload Evaluation Criteria (see Section 2.3).

Figure 72 shows these areas and their inputs to the workload analysis.



11 April 1975

Figure 72
Pilot Workload Analysis

Calculation of pilot workload made use of the MCAIR Pilot Simulation Model, References (26) and (27).

2.20.3 WORKLOAD RESULTS - Workload data were analyzed for both static and dynamic simulations and comparisons made as illustrated in Figure 73. Direct comparison between the dynamic DFCS evaluation and dynamic advanced fighter were not possible due to a lack of dynamic workload data for the advanced fighter.

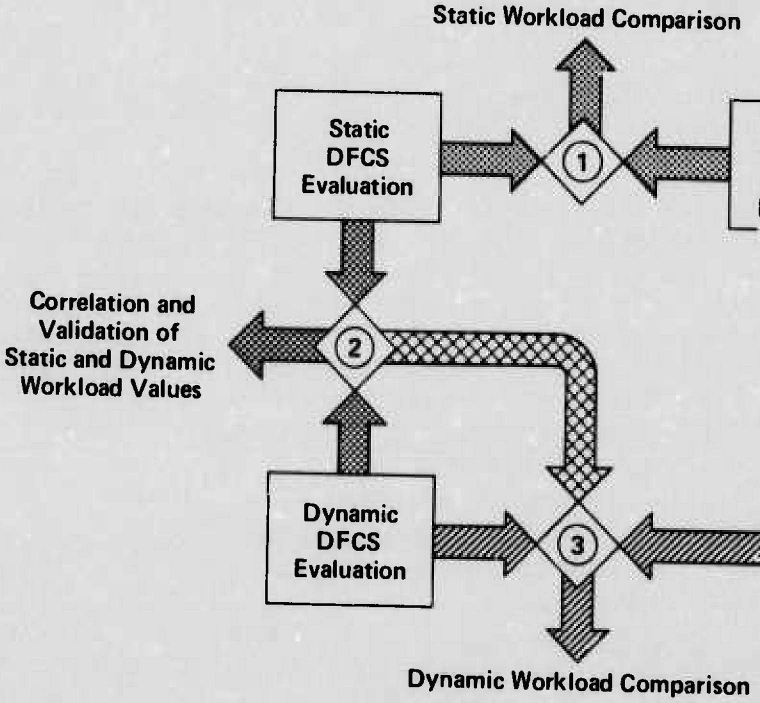


Figure 73
Pilot Workload Data Comparisons

The static simulation, consisting of a design aid evaluation, is described in Section 3.2. Data gathered from this evaluation were used for workload calculations for both the DFCS and Advanced Fighter configurations. Comparison was then made between the results of these two static simulations.

Dynamic simulation provided man-in-the-loop data which was used for workload calculation of the DFCS configuration. These workload calculations were used first to find what, if any, correlation existed with the static DFCS workload data. A high correlation would show validity between the two methods of workload calculations; static and dynamic. Comparisons could then be made between the dynamic DFCS and the static Advanced Fighter.

References: 26. Asiala, C.F., "Digital Simulation Model for Fighter Pilot Workload," Report MDC A0058.

27. Asiala, C.F., "Role of Digital Computer Models in Training Device Design Performance Measures," NAVTRADEVCENIH-206, February 1972.

2.20.3.1 Static Workload Comparisons - Seven of the 14 mission segments described in Section 2.2 were simulated to determine pilot workload. These seven were:

- Takeoff and climb,
- Cruise,
- Air-to-ground attack - Bomb,
- Air-to-air combat - MRM,
- Air-to-air combat - SRM,
- Air-to-air combat - Gun, and
- Approach and landing.

Each of these segments was simulated for both the DFCS and the Advanced Fighter configuration. These simulations were performed using the idealized mission segment task analysis (Section 2.2). Table 30 shows the workload values for the DFCS and Advanced Fighter configurations for the seven simulated mission segments. Values are expressed as a percentage of the time required to perform the mission segment tasks to the time available for those tasks. The total workload has been divided between the four major workload components. The average figure shown is the average of the four workload components.

Table 30
Static Workload Comparisons
DFCS vs Advanced Fighter

Mission Segment	Takeoff and Climb		Cruise		Air-to-Ground Attack (Bomb)		Air-to-Air						Approach and Landing	
							MRM		SRM		Gun			
Aircraft	DFCS	Adv Ftr	DFCS	Adv Ftr	DFCS	Adv Ftr	DFCS	Adv Ftr	DFCS	Adv Ftr	DFCS	Adv Ftr	DFCS	Adv Ftr
Visual	18.6	31.8	28.7	41.6	67.2	71.0	34.3	35.6	55.6	56.4	81.5	82.1	11.2	35.5
Right Hand	7.8	25.5	0.3	8.5	22.3	28.5	23.3	33.9	21.9	32.2	31.0	49.6	0.7	17.6
Left Hand	10.7	16.6	7.2	10.8	31.2	29.7	14.5	12.4	14.2	13.5	15.8	16.1	4.2	8.6
Info Proc	30.8	69.1	32.2	48.1	66.8	68.5	53.2	53.2	76.5	79.3	84.3	84.0	17.4	48.6
Avg	17.0	35.8	17.1	27.3	46.9	49.4	31.3	33.8	42.1	45.4	53.2	58.0	8.4	27.6
Percent Reduced Workload	52.5		37.4		5.1		7.8		7.3		8.3		69.6	

The bottom line of Table 30 shows the percentage by which the average Advanced Fighter workload was reduced by the DFCS configuration. It is calculated as:

$$\frac{\text{Advanced Fighter average workload - DFCS average workload}}{\text{Advanced Fighter average workload}}$$

In each of the seven mission segments simulated, the DFCS configuration showed a reduced workload. The greater reductions were found in the non-combat mission segments, namely takeoff and climb, cruise, and approach and landing. The reduction in these segments was a result of the DFCS configurations, e.g.:

- Introduction of a flight management system,
- Establishment of a simple, effective means of communication between the flight management computer and the pilot,
- Introduction of advanced displays which centralized primary flight information,
- Use of a side stick controller, and
- Incorporation of pilot-relief modes, e.g., Attitude, Heading, and Altitude Hold, Lateral and Vertical Navigation and Auto ILS Modes.

2.20.3.2 <u>Correlation and Validation of Static and Dynamic Workload Values</u> - The pilot task logic networks were revised to accept the dynamic simulation data and to conform to the actual mission segment events as they were flown in the Integrated Control Law and Display Simulation (Section 3.3). Only the DFCS configuration was flown in this simulation.

Table 31 shows the dynamic DFCS workload results for the same seven mission segments as used in the preceding section, and compared with values from the DFCS configuration static workload simulation. This table shows good agreement between the average workload results for dynamic and static simulations for each of the seven segments examined.

Table 31
DFCS Static and Dynamic Workload Comparison

	Takeoff		Cruise		AG Bomb		ACM MRM		ACM SRM		ACM GUN		LANDING	
	S	D	S	D	S	D	S	D	S	D	S	D	S	D
Visual	18.8	19.5	22.1	21.8	67.3	66.4	34.3	28.8	55.6	48.1	81.5	87.4	13.2	15.5
Right Hand	8.9	11.7	3.1	3.7	22.3	23.5	23.3	29.9	21.9	27.1	31.0	32.7	2.4	3.0
Left Hand	7.6	11.8	6.8	6.7	31.3	38.9	14.5	15.1	14.2	15.9	15.8	18.4	8.9	10.0
IP	27.0	26.5	24.4	21.9	67.7	64.6	53.2	46.0	76.5	68.9	84.3	88.0	24.4	22.3
Avg	15.6	17.4	14.1	13.5	47.2	48.4	31.3	30.0	42.1	40.0	53.2	56.6	12.2	12.7

S = Static, Digital Simulation
IP = Information Processing
D = Dynamic, Man-in-the-Loop Simulation

Note: Static Values do not correspond to those shown on Table 30 due to changes in pilot task logic networks necessary for correspondence with tasks performed in dynamic simulation.

Correlation coefficients (r = Pearson product-moment) were calculated from the data presented in Table 31 for each of the sensory modes and their average across the seven mission segments. The results were:

o visual	r = 0.902
o right hand	r = 0.986
o left hand	r = 0.987
o information processing	r = 0.989
o average workload	r = 0.995

Since the range of the correlation coefficient is from -1.0 to +1.0, the results shown above indicate a high positive correlation in each area. This shows that the static workload results were, in fact, a good predictor of what would be found when actual man-in-the-loop simulation data was used in the generation of workload results.

The high positive correlations provided validation of the static workload results as good predictors of dynamic workload and permitted the comparison between the dynamic DFCS and static Advanced Fighter workload results presented in the next section.

2.20.3.3 <u>Dynamic Workload Comparison</u> - Comparison of average workload data for the dynamic DFCS and the static Advanced Fighter are shown in Figure 74. A reduction in workload is shown for the DFCS in each of the seven mission segments. Greatest workload savings are found in the takeoff and climb, cruise, and approach and landing segments.

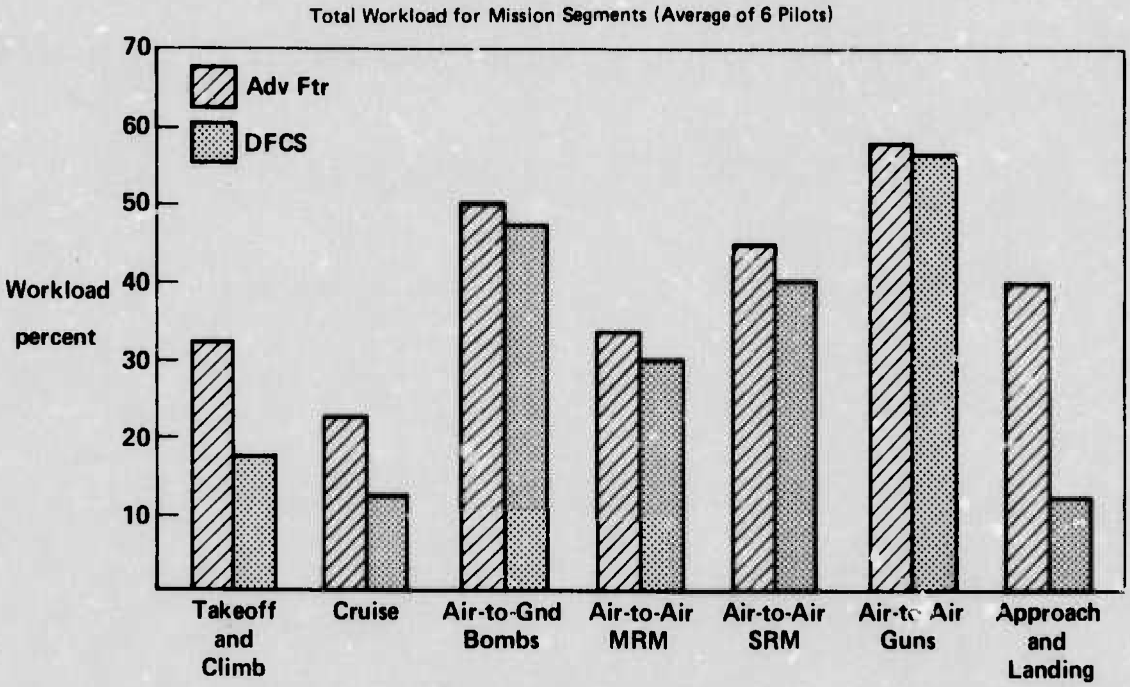


Figure 74
Workload Results
DFCS vs Advanced Fighter

2.20.4 CONCLUSIONS - The following conclusions have been drawn from the preceding comparisons of pilot workload for the DFCS equipped aircraft to that for the advanced fighter.

- The DFCS configuration showed a reduced workload in each of the seven segments simulated.
- Reduced pilot workload resulted primarily from the introduction of a flight management system by establishing:
    - Simple, effective means of communication between the flight management computer and the pilot,
    - Eliminating routine tasks traditionally performed by pilots,
    - Restructuring the information available for the decision process,
    - Automation of the flight activities through pilot-relief modes, and
    - Integration of flight control modes with relevant display formats.
- Steps were taken toward making the pilot a mission-oriented manager rather than a subsystem operator.

2.21 SURVIVABILITY ANALYSIS

A survivability analysis was conducted for each of the three sound candidate configurations considered during the study. The analysis employed survivability logic diagrams (SLD) and the computer program developed in the Survivability Assessment Guidelines for Flight Control Systems (SAG-FCS) study for AFFDL, Reference (28). The threats and flight profiles used to determine projectile hit densities and striking velocities were the same as those used in the SFCS survivability analysis, Reference (29). The SLDs replace the killing combination charts (dot charts) used in the Reference (29) survivability analysis, and define combinations of critical components which must survive for the aircraft to survive. A flight control system loss comparison among the F-4E, SFCS and DFCS configurations is presented in Figure 75. These data are presented for 15 degree dive angle attacks against a 23mm defense with a "3 scaled" density as defined in Reference (29).

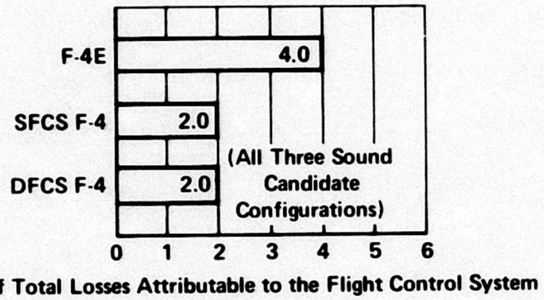


Figure 75
Flight Control System Loss Comparison
23 mm Defense 15° Dive

Conclusion

The survivability analysis showed no significant survivability differences among the three sound candidate configurations.

References: 28. AFFDL-TR-74-39 Vol I, "Survivability Assessment Guidelines for Flight Control Systems", June 1974.

29. AFFDL-TR-73-105 Supplement 1, "Survivable Flight Control System Final Report, Supplement for Survivability Analysis", December 1973 (Confidential).

2.22 COST-OF-OWNERSHIP ANALYSIS

The three sound candidate DFCS configurations, excluding the displays and controllers, were analyzed for total cost-of-ownership. The DFCS was assumed to be a subsystem of the aircraft in a TAC fighter squadron. The squadron was assumed to consist of 24 aircraft which flew 45 hours per month for 10 years, with 50% overseas and 50% Continental U.S. Mean time between unscheduled maintenance action and maintenance manhours per operating hour were estimated for each configuration. Operations and Maintenance (O&M) costs were estimated for a squadron for 10 years. Optimum Repair Level Analysis (ORLA) equations for the major cost generating categories were modified to express these costs as functions of maintenance manhours per operating hour, ratio of operating hours to flight hours, unit cost per configuration, mean time between unscheduled maintenance actions off aircraft and configuration weight. Acquisition costs were calculated from standard cost estimating relationships that have been developed for costing subsystems of advanced design aircraft; these include RDT&E and investment. Investment cost calculations were based on an assumed buy of 720 aircraft sets.

Table 32 shows the relative cost of Configurations B and C normalized to Configuration A. Also shown in Table 32 are the relative acquisition and relative ten year operations and maintenance costs for each configuration normalized to Configuration A.

Table 32
Relative Cost-of-Ownership Acquisition and Ten Year O&M Cost

Configuration	Relative Acquisition Cost	Relative Ten Year O&M Cost	Relative Cost of Ownership
A	0.37	0.63	1.00
B	0.45	0.90	1.35
C	0.44	0.98	1.42

CONCLUSION

The conclusion of the cost-of-ownership analysis is that Configuration A has the least total cost.

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3.0 DESIGN AID AND SIMULATIONS

3.1 GENERAL

This section describes the cockpit mockup, design aid and man-in-loop simulation efforts performed during the DFCS definition study. Iterative evaluations using these laboratory tools helped to define an acceptable cockpit arrangement, flight control laws, and compatible displays and controllers, and to determine their effects on pilot workload and mission effectiveness. Twelve customer pilots, Table 33, participated in design aid and simulation evaluations conducted during the time period June 1974 through January 1975, Figure 76.

Table 33
Evaluation Pilots

Name and Activity	No. Fighter Type A/C Flown	Total No. Flt Hours	Combat Experience	Special Experience	Simulation Participation		
					Design Aid	Control Law	Integrated CL & Displ
Larry A. Walker Capt. USMC NATC Pax River	6	1983	150 A/G Missions	HUD Side Stick	✓	✓	✓
Sam Herron AFFDL, W/P AFB	3	4850	100 Recon Missions		✓	–	✓
Doyle Borchers LCDR USN VF-124, Miramar NAS	6	1680	130 Strike Missions over N. Vietnam	HUD Over 300 Carrier Landings	✓	–	✓
V.L. Strock Capt. USAF 1 FC, Randolph AFB	2	1800	Vietnam Tour		✓	–	–
R.K. Johnson Major USMC NATC Pax River	12	4600	100 Cap & ECM Escort Missions 225 Night All Weather Attack Missions	HUD 700 Carrier Landings	✓	–	–
Richard M. Cooper Major USAF TPS Edwards AFB	3	3200	550 Missions (260 Over N. Vietnam) 1200 Combat Hours	Side Stick Cont in F-104	✓	–	–
John Hoffman Major USAF 6512 Test Sq., Edwards AFB	5	2723	388 Hours (F-105 A/G Missions)	HUD	–	✓	✓
Duane Zeig Major USAF 4950 Test Wg. W/P AFB	4	2300	100 A/G Missions in F-105		–	✓	–
John B. McDonald Major USAF FTC Edwards AFB	6	3974	Vietnam Tour in F-4	Side Stick Cont in F-104	–	✓	–
Barry Gastrock LCDR USN NATC Pax River	9	2365	135 A/G Missions 80 - Photo Recon Missions	HUD	–	✓	✓
Richard E. Lawyer Lt. Col. USAF Ftr Ops Kirtland AFB	11	5200	Vietnam Tour	Side Stick Cont in F-101 & F-104	–	–	✓
Robert Ettinger Major USAF FTP Operations, Edwards AFB	7	3242	Vietnam Tour in F-4	Side Stick Cont in NF-106, F-104, F4 (SFCS & PACT), NT-33 & YF-16	–	–	✓

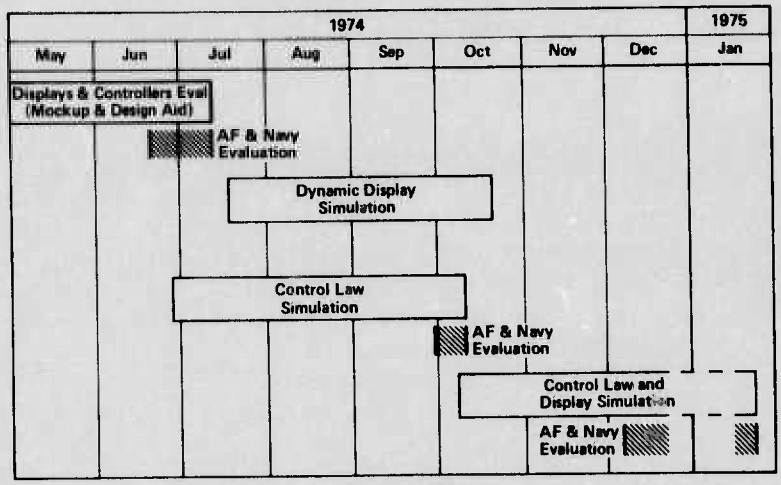


Figure 76
Timing of Design Aid and Simulations

This section discusses design aid and simulation activities under the following subsections:

- Cockpit Design Aid and Mockup
  - Design Aid
  - Static Mockup
  - Configuration Evaluation
- Simulations
  - Control Law
  - Dynamic Displays
  - Integrated Control Law and Display

3.2 COCKPIT DESIGN AID AND MOCKUP

A design aid was developed which was representative of the Digital FCS displays and controllers arrangement as it evolved. An existing mockup, which was representative of a single place advanced tactical fighter, was utilized. Both the design aid and the mockup were used for Digital FCS display and controller evaluations by pilots and engineering psychologists and physiologists.

3.2.1 DESIGN AID - A full-scale design aid was built to F-4 front cockpit dimensions. Installed in the design aid was a standard F-4 ejection seat, and the DFCS displays and controllers arrangements developed during the analyses. The design aid was constructed from foam core and wood to permit rapid reconfiguration as the design progressed. The displays, instruments, and switches were, in general, represented by drawings, photographs, and mockups. An SSC and a throttle assembly were mounted on the seat. Figure 77 presents the design aid which evolved through successive iterations during the static evaluation.

Subsequently, the design aid was modified to accept the actual DFCS displays, controllers, and other hardware and used during the Integrated Control Law and Display Simulation.

3.2.2 STATIC MOCKUP - An existing full scale static mockup which was representative of a single place advanced tactical fighter was used to establish baseline data for the pilot workload analysis. Figure 78 provides a view of the advanced fighter static mockup.

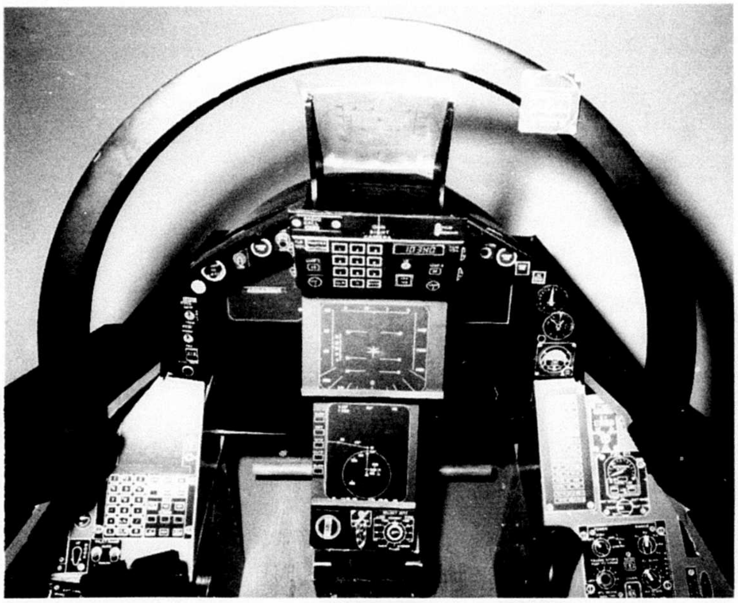


Figure 77
DFCS Design Aid

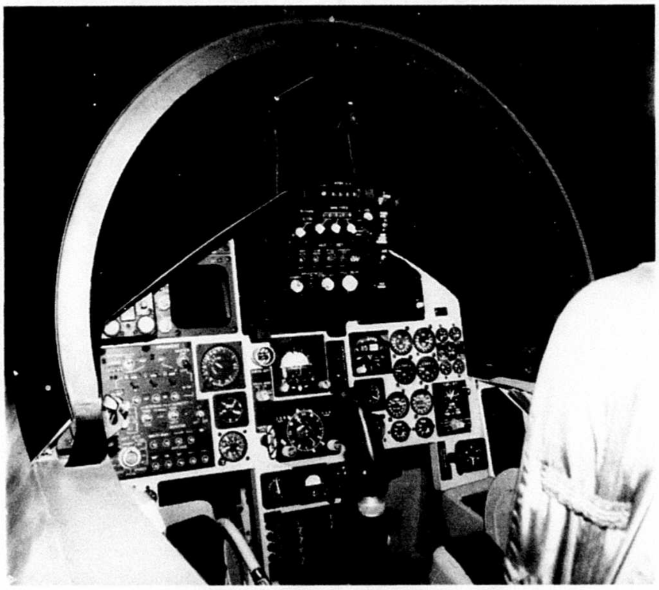


Figure 78
Static Mockup
Advanced Fighter

3.2.3 CONFIGURATION EVALUATION - Six experienced fighter pilots, two each from the Air Force, Navy, and Marine Corps, participated in the configuration evaluations. Evaluations were performed using the static mockup and the DFCS design aid to verify the acceptability of the cockpit geometry; and to determine the ease and speed of the pilot's movements in performance of operational tasks. The mission scenario was exercised and qualitative assessments were made to determine whether each task could be performed. The time required to perform selected tasks was recorded for use in the pilot workload analysis discussed in Section 2.20. The evaluation was conducted by using the following techniques:

- Pilot briefing,
- Pilot background questionnaire,
- Pilot anthropometry,
- Task performance,
- Mission scenario analysis,
- Questionnaire, and
- Pilot critique and debriefing.

A brief description of each of the above techniques is provided in the following paragraphs.

3.2.3.1 Pilot Briefing - During this briefing, the pilots were familiarized with the general objectives of the evaluation and the evaluation plan. An overview of the program, aircraft operational features and crew station design were presented.

3.2.3.2 Pilot Background Questionnaire - This questionnaire was a written list of short-answer questions formulated to ascertain pilot experience in a variety of areas. These areas included:

- Type of aircraft flown,
- Aircraft currency,
- Aircraft experience (log hours),
- Air combat experience, and
- Air-to-ground weapons delivery experience.

The answers to these questions showed the high quality and diversification of pilot experience applied to this evaluation.

3.2.3.3 Anthropometric Measurements - Anthropometric measurements were taken for each pilot. The measurements were made to determine the relative pilot size for such dimensions as sitting eye height and reach distance. Each pilot's capability to reach and operate controllers and instruments was then evaluated.

Measurements using anthropometric measurement instruments were made on each pilot wearing his flight suit. In all cases, the pilot either stood or sat in an erect manner. In general, the six pilots were in the 50th - 99th percentile range which provided adequate evaluation by large pilots.

Measurements were also taken on four additional pilots during the Control Law Simulation. The measurements of two of these pilots are representative of the lower percentiles, 5th - 50th, and provided adequate evaluation by small pilots.

3.2.3.4 Task Performance - Pilot performance of flight tasks were measured and recorded. The pilot was seated in the Digital FCS design aid, wearing standard flight equipment. He was instructed to perform a specific task as quickly as possible. Each task started from a neutral position with the left hand on the throttles and the right hand on the flight controller. The elapsed time beginning from and returning to the neutral position was measured with a stop watch. Tasks required to perform the same functions were timed in the advanced fighter mockup. Task times from both arrangements were used in the static and dynamic workload analysis.

3.2.3.5 Mission Scenario Analysis - Task evaluation based upon the mission scenario segments was performed in both the Digital FCS design aid and the advanced fighter mockup. Comments on tasks performed by pilots were recorded. These data included pilot opinions as to the appropriateness of the mission scenario task identification. The purpose of this activity was to allow the pilot to "fly" the aircraft through a complete mission in order to determine if the controllers and displays in the crew station were adequate to accomplish the tasks required of the pilot. The mission scenario included all fourteen mission segments described in Section 2. The pilot was "talked through" each of these segments. He operated the controls as required and reach capability in the crew station was noted.

The six pilots found the mission scenario and tasks to be realistic. All gave tentative approval of the DFCS crew station design and concepts for such a mission. This approval was dependent upon simulated and actual flight testing. No major reach problems were observed with any pilot.

Questionnaires - Pilots were given questionnaires comparing different concepts within and between the two crew stations. Table 34 lists the questions and the pilot selections, which compared the DFCS crew station with tne advanced fighter. The number of pilots selecting a specific concept is noted adjacent to the concept. The total of pilot selections for each arrangement is noted at the end of the list and demonstrates a strong preference for the DFCS arrangement.

3.2.3.7 Pilot Critique and Debriefing - In the pilot critique each pilot was asked to candidly critique the Digital FCS design aid. The pilot sat in the design aid and was encouraged to give his opinions and ideas on the cockpit layout and the controller and design concept. He was also asked to respond to a number of prepared questions covering the relevant areas of the cockpit arrangement.

A debriefing was conducted at the end of each evaluation in which all pilots were interviewed together. This debriefing was an open exchange of ideas and comments related to the design aid arrangements and the evaluation procedure.

3.2.3.8 Conclusion - The configuration evaluation was conducted using the Digital FCS design aid and the advanced fighter mockup. Six pilots from the Air Force, Navy, and Marine Corps participated in three separate displays and controllers evaluations. Data collected from pilot background questionnaires, anthropometric measurements, paired comparison questionnaires, and pilot critiques and debriefings

Table 34
Pilot Opinions of DFCS vs Advanced Fighter

	DFCS	△1	Advanced Fighter	△1
1. Communication Control Location	Main Panel Top Center	4	Left Console	2
2. Communication Control Type	Keyboard	5	Thumbwheel	1
3. Radar Control Panel Location	Right Console - Fwd	3	Left Console	3
4. Throttle Location	Seat Armrest	5	Left Console	1
5. Throttle Throw	Short (6 in.) Throw	6	Conventional	0
6. Select Jettison Control Location	Center Lower Main Panel	3	Left Main Panel	3
7. HUD Control Panel Location	Left Console	1	Top Center Main Panel	5
8. Radar Display	Time - Shared	6	Dedicated	0
9. Threat Information Display	Time - Shared	5	Dedicated	1
10. Standby Instrument Location	Right Main Panel	0	Lower Center Main Panel	6
11. Fuel Quantity Gauge Location	Right Console - Fwd	3	Right Main Panel	3
12. Navigation Control Panel	Integrated	4	Dedicated	2
13. Navigation Control Panel Location	Left Console - Fwd	3	Right Console - Center	3
14. Navigation Display (Horizontal Situation) Type	Time - Shared	4	Dedicated	2
15. Flight Controller Location	Side Arm	4	Center	2
Totals		56		34

△1 Number of pilots who preferred this concept

were used to verify the acceptability of the cockpit arrangement and to make changes where indicated. Task performance data was taken and used in the workload analysis.

No major reach problems were observed and each pilot generally approved of the DFCS crew station design and concepts.

3.3 SIMULATIONS

Three man-in-the-loop simulations were performed to evaluate, refine, and verify the control laws, displays and controllers discussed in Section 2. The three simulations were the:

- Control Law Simulation,
- Dynamic Display Simulation, and
- Integrated Control Law and Display Simulation.

These iterative simulations were structured so as to converge on the most effective combination of the control laws, displays and controllers for the DFCS ADP definition.

The objectives of these simulations were to determine:

- The soundness of the basic DFCS concept,
- Pilot acceptance of changes in flying qualities and displays as a function of mission segment, and
- Benefits in terms of improved weapon delivery accuracy and reduced pilot workload that would be realized using multimode control laws and mode-related advanced displays.

3.3.1 CONTROL LAW SIMULATION

3.3.1.1 Simulation Setup - The SFCS Flight Simulator, modified to include symmetrically and differentially operable horizontal canards, was utilized for this simulation. The cockpit was fitted with a modified SFCS base-pivot SSC attached to the right side of the seat. The cockpit displays included a fixed reticle HUD and the conventional pilot displays such as the ADI, altimeter, Mach meter, etc. The out-of-the-window displays changed as required to provide for field takeoff and landing, cruise, air-to-air combat, air-to-ground weapons delivery, and aircraft carrier landing.

The basic airframe math model consisted of a set of non-linear differential equations in six-degrees-of-freedom representing the motion of the aircraft subject to large angle perturbations. Continuous flight throughout the flight envelope of the "test case" aircraft was possible.

3.3.1.2 Simulation Methods and Results - The specific objectives of the Control Law Simulation were the evaluation and refinement of the DFCS, pilot-assist modes. Emphasis was placed on improvements in weapon delivery accuracy that could be realized with multimode control laws as determined from qualitative pilot opinion and quantitative measurement of the effectiveness and workload parameters as described in Section 2. The pilot-assist modes evaluated during the Control Law Simulation were:

- Normal Mode
- Fixed Canards Mode
- Manual Carrier Landing Mode
- DigiPACT Mode
- Air-to-Air Combat Mode
- Air Combat Mode (ACM)
- Air-to-Ground Gunnery Mode
- Air-to-Ground Bombing Mode

The Normal, Fixed Canards and Manual Carrier Landing Modes were evaluated to determine handling qualities characteristics. Refinements were made to these control laws to effect improvements in pilot ratings of these modes.

The evaluation and refinement of the weapons delivery modes were directed at increasing weapon delivery effectiveness and reducing pilot workload during the performance of the weapons delivery mission segments. Each of these segments were flown with the appropriate weapon delivery mode, the Normal Mode and the DigiPACT Mode.

MCAIR, Air Force, Marine and Navy pilots participated in the Control Law Simulation with the MCAIR pilots completing the initial evaluations and refinements, and the customer pilots participating in the final evaluation from 30 September through 11 October 1974. Each customer pilot participated in the simulation for one week. The week began with a briefing on the control laws and followed with familiarization sessions on the simulator. At mid-week, effectiveness and workload data were recorded and an informal debriefing held during which the evaluation pilots suggested modifications they wished to evaluate to improve effectiveness and handling qualities. Those modifications which could be readily implemented during the simulation evaluation, or which could be implemented on an overnight basis were evaluated on Thursday and Friday, and a final set of effectiveness and workload data were recorded. A formal debriefing was held on Friday.

The pilots felt that a significant learning curve existed which greatly influenced pilot proficiency and that after one week of simulation only a minimum proficiency level was attained. However, basic aircraft control improved on a session-by-session basis, allowing for a more critical analysis and evaluation near the end of each week. All pilots agreed that the concept of multimodes is viable and results in increased mission effectiveness. A thorough evaluation of these modes was hindered by excessive roll sensitivity in all modes and insufficient adjustability of the side stick controller. In an attempt to lessen these problems, combinations of the following modifications were incorporated into the system for further evaluation during the latter part of each week:

- Increased lateral SSC breakout forces,
- Reduced lateral prefilter gain,
- Reshaped lateral stick shaping curve, and
- Reduced lateral prefilter time constant.

These modifications provided a noticeable improvement in both the handling qualities and the weapons delivery effectiveness, but the pilots believed that further improvement could be obtained. A general pilot consensus was that a wider range of adjustability afforded to the armrests and the stick and throttle assemblies would increase controllability and improve the handling qualities. These modifications could not be performed within the schedule available for the Control Law Simulation, however, they were performed later.

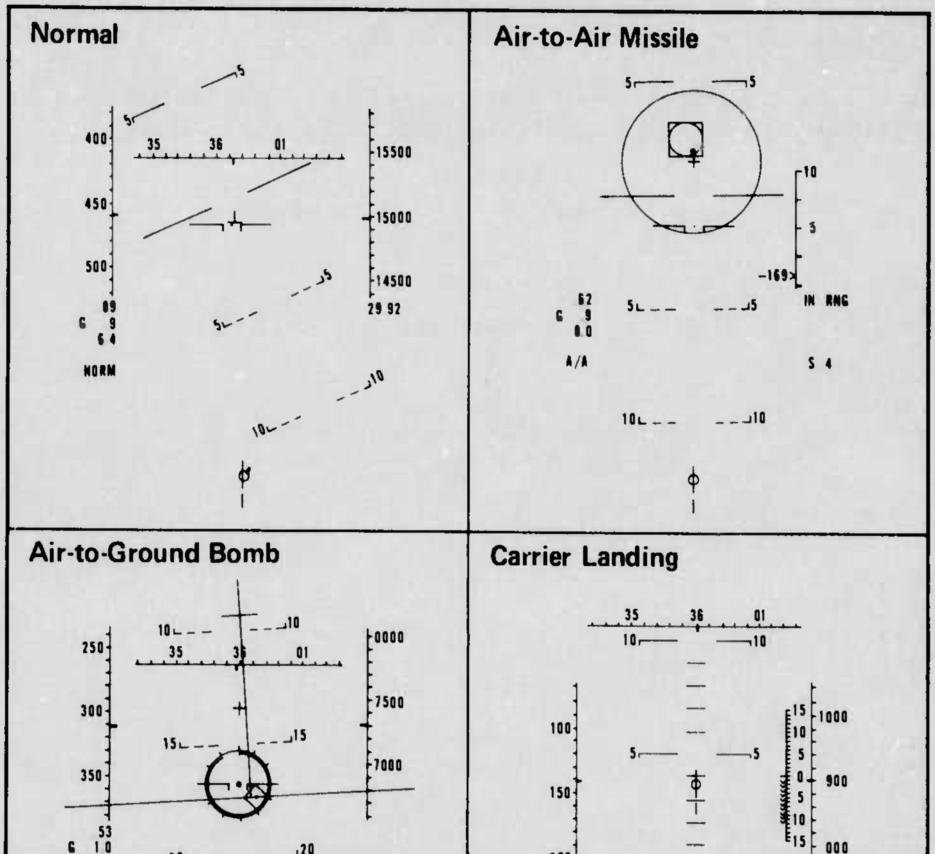
Two separate modes, the Air-to-Air Combat Mode and the Air Combat Mode (ACM), were developed and evaluated for the air-to-air mission segment. All of the evaluation pilots felt that the ACM provided better tracking in the air-to-air mission segment than the Air-to-Air Combat Mode. Consequently, the Air-to-Air Combat Mode was dropped from further consideration.

The special features of DLC, Lateral Translation and Flat Turn integral to the air-to-ground weapons delivery modes, were considered assets to the weapons delivery solution. The DLC, however, produced only a slight effect on aircraft flight path. In response to the pilot's request for more DLC authority, the ailerons and spoilers were programmed to assist the canards and stabilator for producing direct lift. This modification was incorporated into the control laws between simulations and evaluated during the Integrated Control Law and Display Simulation discussed in Section 3.3.3.

3.3.2 DYNAMIC DISPLAY SIMULATION - Dynamic Display Simulations were conducted on the Information Display Incorporated Input Output Machine, (IDIIOM). The initial set of symbology and formats, established by analysis, was programmed into the IDIIOM for review and evaluation. Special purpose programs were used which permitted controlling the individual symbols from the IDIIOM keyboard. Also a digital replayable tape was made which was played through the IDIIOM to demonstrate HUD and MFD I symbology and formats under dynamic conditions.

As a result of the dynamic display simulation, some changes were made to the symbology and the alphanumeric window allocations were redefined. Switching logic was then developed which provided the appropriate display presentation automatically with the selection of a flight control mode.

Figure 79 shows some flight control mode-related displays presented on the HUD. Figure 80 shows a flight control mode related display presented on the MFD I. Figure 81 shows display formats and symbology such as presented on the MFD II.



Normal

Air-to-Air Missile

Air-to-Ground Bomb

Carrier Landing

Evaluated by Man-in-Loop Simulation

Figure 79
Flight Control Mode Related Displays

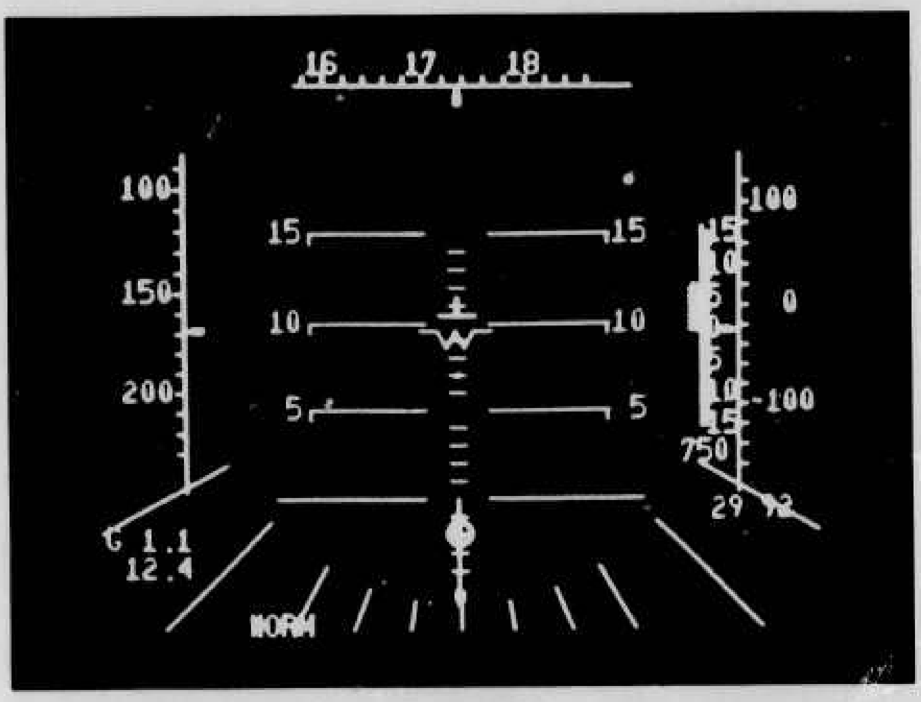


Figure 80
MFD I Display Format for Normal Mode

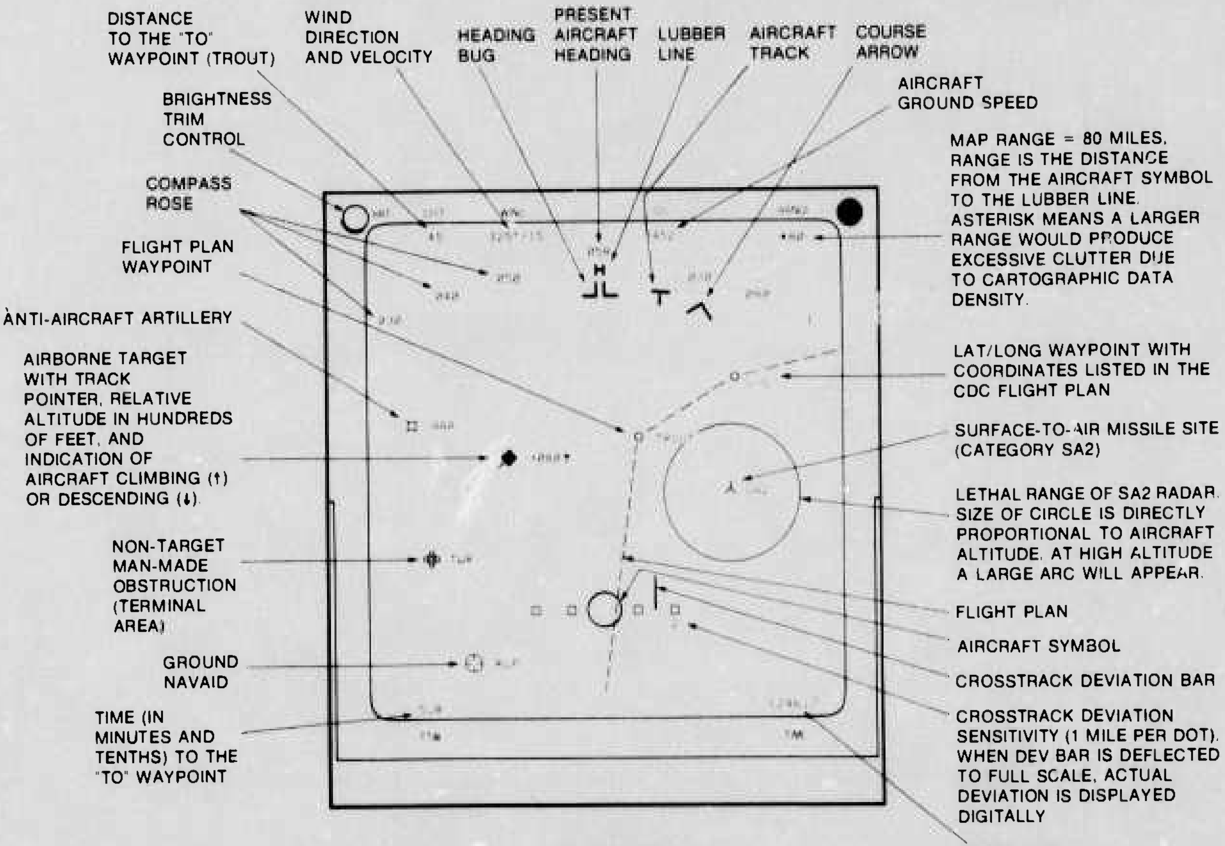


Figure 81
MFD II Format and Symbology

3.3.3 INTEGRATED CONTROL LAW AND DISPLAY SIMULATION

3.3.3.1 Simulation Setup - The Integrated Control Law and Display Simulation utilized the Manned Air Combat Simulator (MACS) III. The MACS III is a fixed-base, real time simulator enclosed in a 40-foot diameter spherical dome which is used as a projection screen for out-of-the-window displays. The out-of-the-window displays included a horizon, aircraft carrier, target aircraft for air-to-air combat and runway used for air-to-ground weapon delivery and takeoff and landing. The cockpit included a HUD, MFD I, MFD II, Computer and Display Controller, armrest mounted throttles and SSC arranged as described in Figure 82. The basic airframe math model was the same as that employed in the Control Law Simulation with the addition of math models of the actuators which were flight hardware in the SFCS Flight Simulator.

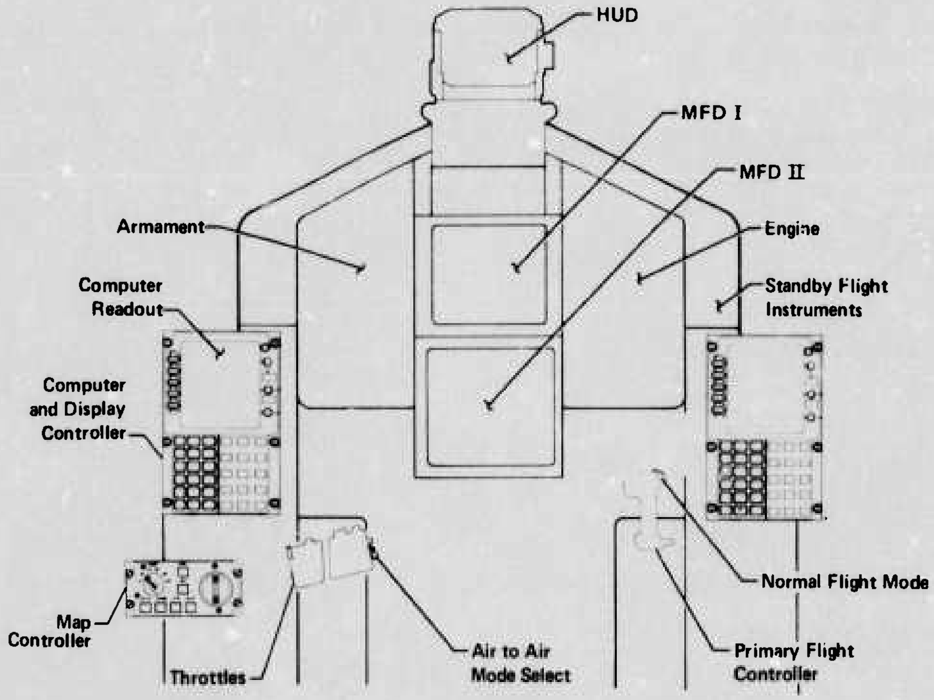


Figure 82
Cockpit Arrangement of Mode Related Displays and Controllers

Major changes made to the control laws and controllers since the Control Law Simulation were:

- Replacement of the modified SFCS base-pivot SSC with a laboratory-model palm-pivot SSC,
- Increased adjustability for the throttles, SSC, and controller armrests,
- Desensitization of the lateral control,
- Addition of symmetrical ailerons and spoilers to the DLC, and
- Elimination of the Air-to-Air Combat Mode.

3.3.3.2 Simulation Methods and Results - The objectives of the Integrated Control Law and Display Simulation were those objectives stated in Section 3.3. These objectives were realized through the performance of individual mission segments and the complete mission scenario utilizing all control modes and related displays except for Automatic ILS and Automatic Energy Management which were not evaluated during these man-in-the-loop simulations. The DFCS Mission Scenario - Mission Flight Plan used during the simulation is shown in Figure 83.

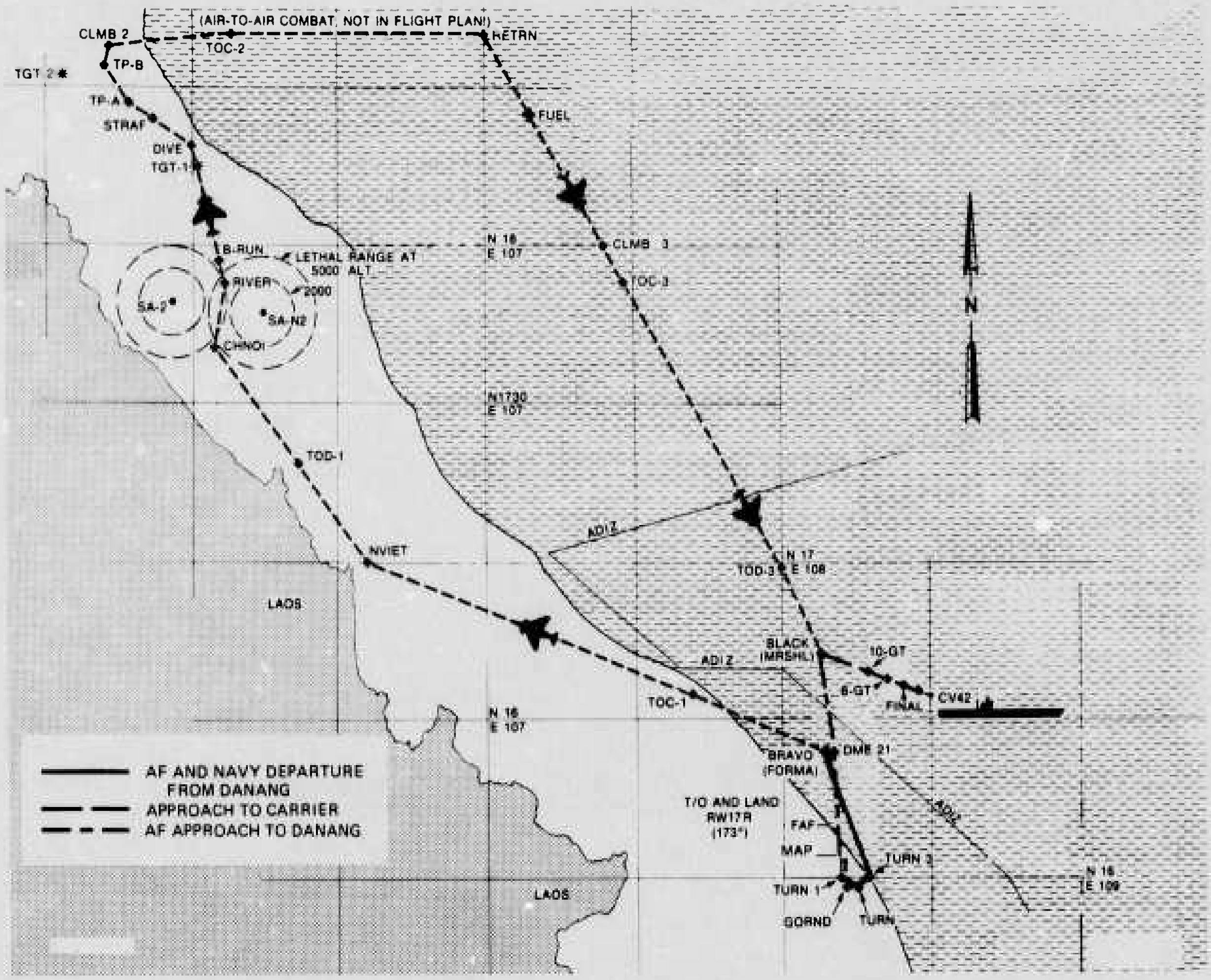


Figure 83
DFCS Mission Scenario - Mission Flight Plan
Lateral Path

Three Air Force, one Marine, two Navy and one civilian in addition to MCAIR pilots participated in the simulation. The customer pilot evaluations were conducted in three, one-week periods between 9 December 1974 and 17 January 1975. The simulation was conducted in a manner similar to the Control Law Simulation with each pilot participating in the simulation for one week which included periods of briefings, familiarization sessions on the simulator, data taking sessions and debriefings. Three of the seven customer pilots had also participated in the earlier Control Law Simulation.

The pilots felt that the basic DFCS concept of multimodes and related displays was shown to increase effectiveness and reduce workload although the problem of lateral sensitivity had not been completely eliminated in this simulation.

Two of three pilots who participated in both the Control Law and the Integrated Control Law and Display Simulations felt that the laboratory-model palm-pivot SSC was an improvement over the modified SFCS base-pivot SSC used in the Control Law Simulation, and that they could track better with it. However, these pilots did not have the opportunity to use the modified base-pivot SSC with its greater range of adjustability. Three other pilots, including one who had participated in the Control Law Simulation, had difficulty controlling the aircraft and tracking a target in the air-to-air mission segment with the laboratory-model palm-pivot SSC. On the last day of the simulation, these pilots were given the opportunity to track with the SFCS base-pivot SSC. Statistical tracking data were not recorded for these evaluations, but the tracking was visually observed to be significantly improved with the base pivot SSC, and the pilots stated their preference for the base-pivot SSC in the final debriefing session.

The paraphrased comments of the majority of the evaluation pilots relative to the control modes, displays, primary flight controllers and displays, and controller management are listed in Figure 84.

3.3.4 CONCLUSIONS - Several conclusions can be drawn from these simulations:

- The integration of multimodes and related displays increases effectiveness and reduces workload,
- Pilots will accept changes in aircraft response, controller functions and displays when these changes contribute to increased mission effectiveness and reduced workload, and
- The basic DFCS concepts of multimode control laws and related displays are sound and should be pursued in a flight test program.

Control Modes

- Multimode Control is a Viable Concept and can Result in Increased Mission Effectiveness
- Manual Carrier Landing Mode Could Also be Used for Field Landing
- Air-to-Ground Bombing Mode "Super" with Lateral Translation and Flat Turn
- Air-to-Ground Bombing and Air-to-Ground Gunnery Could be Combined into a Single Air-to-Ground Mode
- Neutral Speed Stability Provided with the Pilot-Assist Modes was Very Desirable
- Flat Turn (Fuselage Aiming) Should be Added to the Air-to-Air Combat Mode
- A Statically Unstable Advanced FBW Aircraft Needs Angle-of-Attack Limiting for Stall Prevention
- A Departure Preventer is not Wanted in the Power Approach Configuration, Would Rather Power Out of a Stall than have the Aircraft Automatically Rotate Nose-Down when Close to the Surface
- Preselect Heading is "Great"
- Pilot-Relief Modes Alleviate Workload
- Pilot-Relief Modes are Desirable in Cross Country and in Controlled Airspace
- Automatic Navigation Would be Very Useful for Reconnaissance
- Maneuvering Ability Needs to be Increased in Automatic Navigation Mode
- Automatic Energy Management is Desirable

Displays

- Vertical Arrangement of HUD and Multi-Function Displays is Satisfactory
- Weapon Delivery Displays were Very Good Except that the HUD Air-to-Ground Bombing Automatic-Display was too Complex
- HUD Information Content and Large Instantaneous Field-of-View were Excellent
- Degree of Display Declutter is Adequate
- Vertical Velocity Should Remain on the HUD During Cruise
- The EADI Presentation Needs Additional Cues to Readily Determine Attitude During Gross Maneuvers
- Area-Navigation Map Display and Automatic-Navigation Capability are Good Concepts
- Minor Symbology Changes are Desirable

Primary Flight Controllers

- Location of the SSC and Throttles was Satisfactory
- In General, the Switches and Buttons on the Throttle were well Located Except that the Reach to the Air-to-Air Combat Mode Select Button was too Long
- Throttle Grips are too Massive
- Short Throw Throttles were Satisfactory in Simulation but Should be Evaluated in Flight
- Provisions for Up and Down Adjustment with the Seat and Adjustable Arm Rests are Needed with Side-Mounted Controllers
- Side Stick Controller Mechanization, e.g., Grip Shape, Travels and Breakout Forces, Needs Improvement

Display and Controller Management

- CDC Location is Satisfactory
- The Concept of Simultaneous Selection of Flight Control Mode and Related Display is "Super"
- The Selection of Air-to-Air Combat Mode with a Switch on the Throttle Grip is "Great"
- The CDC Concept is Outstanding and its Operation is Easy to Learn
- The CDC Display Update Rate Needs to be Increased
- Some Changes in System Logic are Desirable, e.g.,
  - Selection of Normal and Attitude Hold Modes via the CDC Should be Accomplished Using the CDC Line Select Keys
  - Lateral Automatic Navigation Mode Should Remain Engaged During SSC Pitch Corrections
  - Completed Portion of the Flight Plan Should not be Erased

Figure 84
Evaluation Pilots Comments

4.0 ADVANCED DEVELOPMENT PROGRAM (ADP) DEFINITION

4.1 GENERAL

This section is a summary of the recommended Digital FCS ADP Definition. The recommended ADP Definition evolved from the analyses and simulations reported in Sections 2.0 and 3.0 of this report.

4.2 CANDIDATE FLIGHT CONTROL CONFIGURATION

The flight control configuration recommended for the ADP is a triplex arrangement employing cross-channel monitoring for detection of the first failure and in-line monitoring for detection of the second failure.

The configurations which were evaluated in arriving at this recommendation are shown in Figure 85. A summary of the results of the analyses conducted prior to selection of the Triplex Configuration is presented in Table 35.

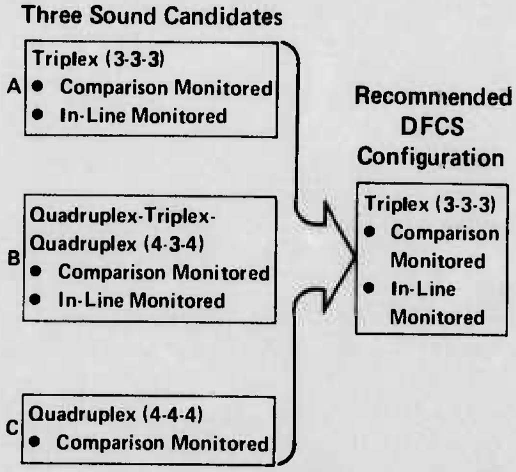


Figure 85
Configuration Development

Table 35
Three Sound Candidates
Summary of Analyses

Configuration	Performance, Safety and Survivability	Raliability (Probability of Loss of Control)	Maintainability (MMH/FH)	Relative Weight	Relative Cost
A (3-3-3)	Sama	3.5×10^{-8}	0.262	1.00	1.00
B (4-3-4)	Same	2.3×10^{-9}	0.298	1.18	1.35
C (4-4-4)	Same	3.9×10^{-10}	0.309	1.18	1.42

4.2.1 SURVIVABLE FLIGHT CONTROL SYSTEM (SFCS) BACK-UP PROVISIONS - It is planned that the quadruplex SFCS, which is currently installed in F4 S/N 62-12200 will be used as a safety back-up for initial flights. The planned arrangement of the SFCS and Digital FCS is illustrated in Figure 86.

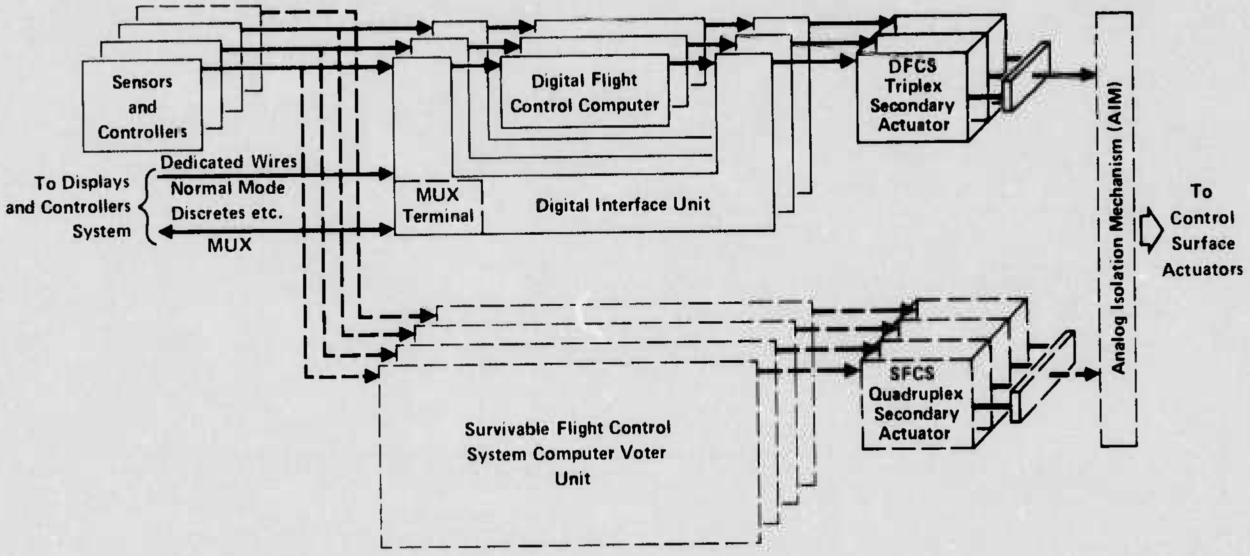


Figure 86
Digital Flight Control System with Survivable Flight Control System Backup

The arrangement of the SFCS and Digital FCS is analogous to the arrangement of the mechanical back-up system and SFCS which was successfully used in Phase IIA of the SFCS Flight Test Program. The Analog Isolation Mechanism (AIM), is a device similar to the one which was used in the SFCS Program. In the SFCS Program it was called a "Mechanical Isolation Mechanism" and it is described in Section 22b.(3) Page 137 of Report AFFDL-TR-71-20 (SFCS Interim Report). It is planned that one AIM will be used in series with the stabilator surface actuator and another in series with the rudder surface actuator. The ailerons will be controlled only by the Digital FCS. This arrangement is also analogous to the SFCS Phase IIA arrangement wherein the ailerons were Fly-By-Wire without mechanical back-up.

After the Digital FCS has been evaluated in flight and found to be safe, it is planned that the SFCS will be removed or disabled.

4.2.2 SALIENT FEATURES OF DIGITAL FCS - Salient features which are planned for implementation in the ADP are listed in Figure 87.

4.2.3 FLIGHT CONTROL MODES - The pilot-assist modes planned for the ADP are listed in Figure 88. Features of the Normal Mode are summarized in Figure 89. Features of the Air-to-Air Combat Mode are summarized in Figure 90. Features of the air-to-ground modes are summarized in Figure 91. The pilot-relief modes recommended for the ADP and other available options are presented in Figure 92.

- Software Voting at Sensor Inputs and Secondary Actuator Commands
- Comparison Monitored for First Failure
- In-Line Monitored for Second Failure
- Actuators Monitored in Software for First and Second Failure
- Outerloop Sensors Tested by Data Reasonableness
- Analog Servo Loop Closure
- DMA Data Exchange Between Digital Flight Control Computers
- Digital Flight Control Computers
  - Frame Synchronized
  - Have Dedicated Power Supplies
  - Self-Tested
- The Emergency Disengage (Paddle) Switch Deenergizes the Canard Shutoff Valves
- Sensors are not Dispersed
- Normal Mode Selection will have Priority Over any Other Mode
- For Initial Flights with SFCS Backup:
  - Longitudinal and Directional Axes use Analog Isolation Mechanisms (AIM)
  - The Emergency Disengage (Paddle) Switch Causes the AIM's to Shift to the Analog Mode
  - No Canard Operation in the SFCS Backup Mode
  - A Modified SFCS Master Control and Display Panel (MCDP) will be Located in a Remote Location
  - A Small Cockpit Mounted Panel which Includes the MCDP Switch and Indicator Functions will be Provided

Figure 87
Salient Features of the Triplex Digital Flight Control System

Evaluated During Man-in-the-Loop Simulations	Recommended for Incorporation Into ADP
● Normal	● Normal(1)
● Gear Up: Cruise	● Gear Up: Cruise
● Gear Down: Airfield Takeoff and Landing	● Gear Down: Airfield and Carrier Takeoff and Landing
● Carrier Takeoff and Landing	
● Air-to-Air Combat	● Air-to-Air Combat
● With Planar Turn	
● Without Planar Turn	● Without Planar Turn
● Air-to-Ground Bombing	● Air-to-Ground Bombing
● Air-to-Ground Gunnery	● Air-to-Ground Gunnery
● Fixed Canards	
● DigiPACT(2)	● DigiPACT(2)

(1) Includes Operable and Fixed Canards

(2) DigiPACT - Digital Implementation of SFCS-PACT Control Laws (Provided for Purposes of Comparison)

Figure 88
Pilot-Assist Modes for the ADP

Gear Up	Gear Down
• Neutral Speed Stability	• Neutral Speed Stability (Disengaged on Landing)
• Direct Lift Control(1)	• Direct Lift Control
• Lateral Translation(1)	• Lateral Translation
• Blended Pitch Rate and N_z (C*) Feedback	• Blended Pitch Rate, N_z and AOA Feedback
• Turn Coordination Using $P \cdot \alpha$ and ARI	• Turn Coordination with ARI
• Departure Prevention	• Departure Prevention

(1) Optimized for the Air Refueling Segment

Figure 89
Features of Normal Mode

- Neutral Speed Stability
- Vertical Fuselage Aiming using the Direct Lift Controller
- Lateral Fuselage Aiming using the Rudder Pedals
- Increased Pitch and Roll Response
- Departure Prevention
- Improved High Angle-of-Attack Performance
    - Blended Pitch Rate and N_z Feedback at Low and Medium AOA
    - Blended Pitch Rate and AOA Feedback at High AOA
    - Turn Coordination
        - ARI
        - β and $\dot{\beta}$ Feedback

Figure 90
Features of Air-to-Air Combat Mode

- Neutral Speed Stability
- Direct Lift Control
- Lateral Translation
- Flat Turn
- Precise Attitude Tracking - Pitch Rate Feedback Only in the Longitudinal Axis
- Longitudinal Axis Reconfigured to Include N_z Feedback above One g Incremental Load Factor
- Gun Reticle or Velocity Vector Stabilized Depending on Weapon Selection
- Departure Prevention

Figure 91
Features of Air-to-Ground Modes

- **Recommended for ADP**
  - Pitch Attitude Hold
  - Roll Attitude or Heading Hold
  - Altitude Hold
  - Preselect Heading
  - Automatic Vertical Navigation
  - Automatic Lateral Navigation

- **Available Options for ADP**
  - Automatic Carrier Landing
  - Automatic ILS
  - Automatic Throttles
  - Automatic Energy Management

Figure 92
Pilot-Relief Modes

4.2.4 CONCLUSION - A recommended Digital FCS flight control configuration has been determined as summarized above. The configuration incorporates the features determined to be necessary or desirable to implement the conclusions of the Digital FCS Analyses and Simulations.

4.3 COMPUTER SELECTION

An investigation of guideline computer characteristics was conducted to aid in selection of an airborne digital flight control computer suitable to implement the recommended Digital FCS ADP configuration. The guideline characteristics, given in Figure 93, are a useful guide in selecting the candidate computers.

- **Status**
  - Flight Worthy and Near Production; Preferably Used in DFCS-Related Applications
- **Support Software and Equipment**
  - Developed and Available; Minimum: Assembler, Simulator, Loader-Verifier, Control Unit
- **Environment**
  - MIL-E-5400, Class 2 Minimum (SL to 70,000 ft, −54° to +71°C)
- **Type**
  - General Purpose, 16-BIT Parallel, Microprogram Control
- **Arithmetic**
  - Fixed Point, Binary, Two's Complement, Double Precision
- **Storage**
  - 24K x 16-BIT Core for Use During Ground Development and Flight Tests with Backup
  - 24K x 16-BIT Prom + 1K x 16-BIT Ram for Use During Flight Tests without Backup
  - 1-Bit Parity
- **Instructions**
  - 43 Basic, Including Double Precision Load, Store, Add, Subtract, Shift,
- **Execution Times**
  - 2 microsecond Add; 7 microsecond Multiply
- **Computational Speed**
  - 200,000 Operations per Second
- **Interrupts**
  - 13 Priority Levels
- **Registers**
  - 16 x 16-BIT Register File, Two of Which can be used as Index Registers
- **Timers**
  - 2 Programmable Timers; 1 Watchdog Timer
- **Input-Output**
  - Program Controlled Input and Output
  - One DME Input Channel
  - Two Input and Output DME Channels
  - 16 Input and Output Discretes
  - 17-Bit Words Including Parity
- **Volume: 0.390 cu ft (Ave with Core)**
- **Weight: 23 lb (Ave with Core)**
- **Power: 160 W (Ave with Core)**

Figure 93
Guideline Characteristics for ADP Computers

Thirty-five computers were then surveyed and their characteristics compiled. The information on some computers was more complete than on others; however, an attempt was made to place all computers on a common basis with respect to type and size of memory before preparing weight, size and power summaries.

Four candidate computers were then selected from the field of surveyed computers.

Conclusions

- o The computers surveyed all fell rather neatly into three weight, volume, and power classes, named Maxi, Midi, and Mini, shown in Tables 36, 37, and 38, respectively.
- o There is at least an approximate correlation between the weight, volume, and power classes, and availability, cost, and computational power (throughput). Figure 94 shows the three classes of computers versus the years in which the computers would likely be selected for use in a Digital FCS ADP. Figure 95 shows the relative cost and throughput and the expected region of operation for the Digital FCS.
- o The characteristics of the four candidate computers are given in Tables 39 and 40. The guideline characteristics are included for purposes of comparison.
- o The candidate computers when configured with a 24K memory, fall in the middle to upper region of the Midi class.
- o The candidate computers can also be configured with semiconductor memories. When so configured, they fall in the lower region of the Midi class.

Table 36
Computer Selection
Computers Surveyed

"Maxi" Class
35 to 60 lb

Computer	Weight* (lb)	Volume* (ft^3)	Power* (W)
Singer SKC-2000	36.0	0.613	355
G.E. MCP-701	54.0	1.070	380
Control Data CDC-5400B	58.0	1.034	300
IBM AP-1	44.5	0.693	220
IBM CP-2	51.0	0.917	270
IBM AP-101	48.0	1.049	350
Sperry 1819A	52.0	0.957	250
Texas Instruments 2540A-2	49.0	1.013	245
Average	49.0	0.920	296

*Based on 24K x 16 BIT Core Memory

Table 37
Computer Selection
Computers Surveyed
"Midi" Class
15 to 30 Lb

Computer	Weight* (lb)	Volume* (ft^3)	Power* (W)
Autonetics D216	15.0	0.194	130
Autonetics D1216	15.0	0.194	130
Bendix BDX-910	28.5	0.487	230
Teledyne TDY-43	28.0	0.507	180
Texas Instruments 2520-2	24.0	0.454	120
Texas Instruments 2520-X	24.0	0.454	120
Delco Magic III	17.5	0.267	168
IBM SP-1	28.1	0.542	147
G.E. MCP-701A (Semiconductor)	18.0	0.300	50
Sperry 1819B	29.0	0.517	180
Sperry RMM-1	23.0	0.347	195
Honeywell HDC-301A	28.0	0.380	120
General Electric CP-16	20.8	0.437	170
Control Data CDC-5400B (Thin Film)	25.0	0.480	50
Control Data CDC-469	15.0	0.145	160
Litton Spirit - II	23.0	0.397	180
Average	23.0	0.390	160

*Based on 24K core memory except as noted in parentheses.

Table 38
Computer Selection
Computers Surveyed
"Mini" Class
Less Than 10 Lb

Computer	Weight* (lb)	Volume* (ft^3)	Power* (W)
Singer SKC-3000	7.50	0.1840	72.0
Singer SKC-2000	8.20	0.2000	87.0
Bunker-Ramo BR-1018	5.00	0.0500	50.0
Lear-Siegler Astro 1601	?	?	?
Hughes HDP-4	6.00	0.0985	50.0
IBM SP-OA	7.26	0.0555	81.0
Delco Magic III (Model 362)	8.30	0.1250	60.0
Delco Magic IV	4.20	0.0810	29.0
Bendix BDX-910	3.90	0.0990	32.5
Autonetics DM 216	4.90	0.0610	44.0
Honeywell HDC-301A	7.80	0.1560	51.0
Average	6.30	0.1100	56.0

*Based on a 16K Semiconductor Memory; Includes CPU, I/O, and Power Supply; Does Not Include Separate Enclosure

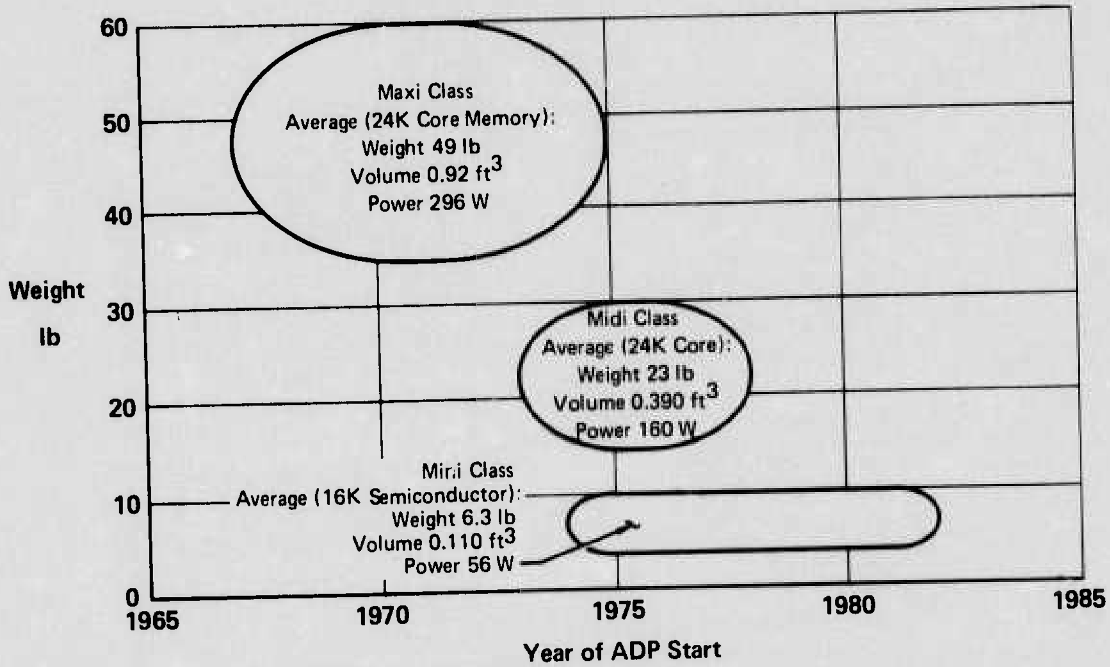


Figure 94
Airborne Computer Trends
Weight, Volume, Power

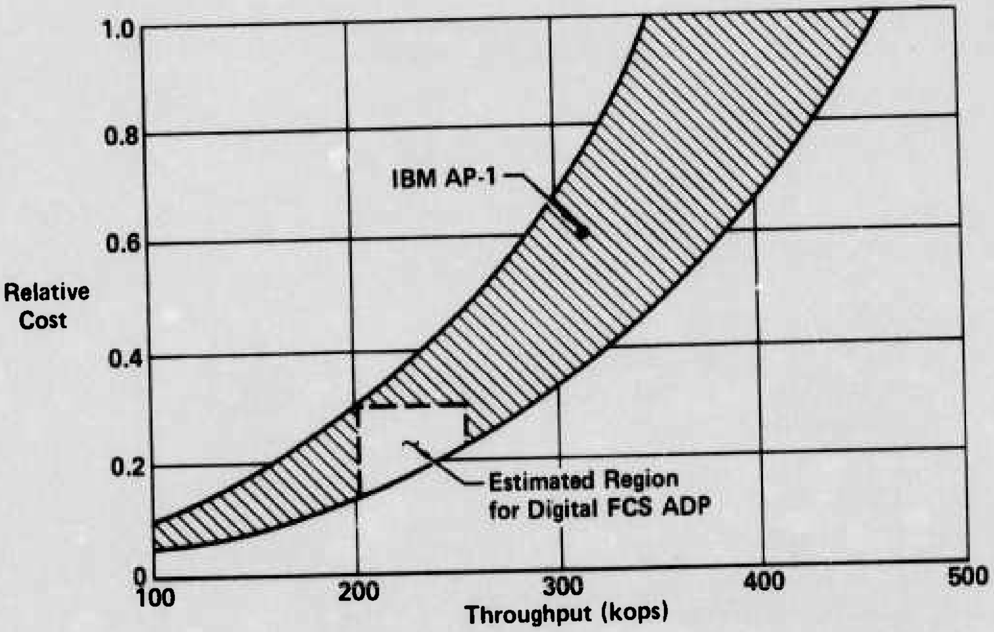


Figure 95
Airborne Computer Trends
Relative Cost vs Throughput

Table 39
Candidate Computers

	Guideline Characteristics	Honeywall HDC - 301A	G.E. MCP - 701A
Status	Flight Worthy and Near Production	SAAB JA-37, A7 Multimode	701 Used on HLH and Dot 727
Control	Micro Program	Hardwired	Microprogram
Wood Length			
• Instruction	16 - BIT	16	16
• Data	16 - BIT	16	16
Storage			
• Core	24 K x 16 BIT	24 K x 16	24 K x 16
• Semiconductor	24-K x 16 Prom, 1 K x 16 Ram	24 K and 1 K	24 K and 2 K
• Parity	1 - BIT	No	Ram has Parity
Instructions	43 Basic	47	104 + 24 Application Dependent
Execution Times			
• Add	2 Microseconds	3	1.75
• Multiply	7 Microseconds	13	5.4
Interrupts	13	2	13 Plus
Registers	16 x 16 BIT File Incl 2 Index	1 Index	3 Index Plus 256 Word Dedicated Ram Scratch Pad
Timers	2 Programmable 1 Watch Dog	1 No	1 1
Input - Output	Programmed Controlled Input-Output	Yes	Yes
	One DMA Input Channel	No	Yes
	Two DMA Input - Output Channels	One	Yes
	16 Input and Output Discretes	12 Input, 10 Output	9 Input, 9 Output
	17-BIT Works Including Parity	No Parity	Yes
Volume	0.390 cu ft (Ave with Core)	0.380	0.300*
Weight	23 lb (Ave with Core)	28	18*
Power	160 W (Ave with Core)	120	50*

*Based on 2K Ram and 24K Rom

All: General Purpose, Parallel, Fixed Point, Binary, Two's Complement, MIL-E-5400, Class E Environment, Support Software and Equipment Available

Table 40
Candidate Computers

	Guideline Characteristics	T.I. 2520-X	Taledyna TDY - 43
Status	Flight Worthy and Near Production	HARM, F-15 TEWS	MBB DFCS
Control	Micro Program	Yes	Yes
Word Length			
• Instruction	16 - BIT	16	16 (20 and 24) Available
• Data	16 - BIT	16 and 32	16
Storage			
• Core	24 K x 16 BIT	24 K x 16	24 K x 16
• Semiconductor	24-K x 16 Prom, 1 K x 16 Ram	24 K and 1 K	24 K and 1 K
• Parity	1 - BIT	Yes	1 - BIT
Instructions	43 Basic	30 Basic, 69 with Extensions	70
Execution Times			
• Add	2 Microseconds	1	2.67
• Multiply	7 Microseconds	6	6.0
Interrupts	13	13	16
Registers	16 x 16 BIT File Incl 2 Index	16 x 16 BIT	16 x 16 BIT 6 Index
Timers	2 Programmable 1 Watch Dog	1 No	No 1
Input - Output	Programmed Controlled Input-Output	Yes	Yes
	One DMA Input Channel	No	Multiport DMA Available
	Two DMA Input-Output Channels	One	
	16 Input and Output Discretes	No	16
	17-BIT Words Including Parity	No Parity	No Parity
Volume	0.390 cu ft (Ave with Core)	0.454	0.507
Weight	23 lb (Ave with Core)	24	28
Power	160 W (Ave with Core)	120	180

All: General Purpose, Parallel, Fixed Point, Binary, Two's Complement, MIL-E-5400, Class 2 Environment, Support Software and Equipment Available

4.4 DISPLAYS AND CONTROLLERS

The display and controller configuration recommended for the ADP is summarized in this section. The display and controller block diagram is presented in Figure 96. The forward cockpit display arrangement is presented in Figure 97. Salient features which are recommended for implementation in the ADP are listed in Figure 98.

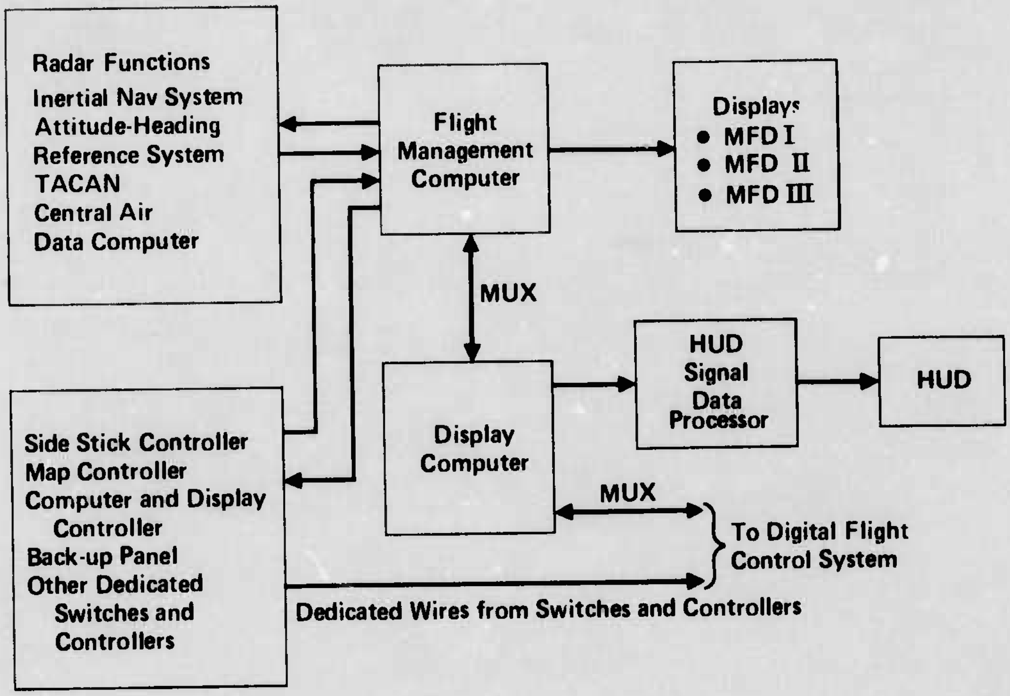


Figure 96
ADP Displays and Controllers

4.5 DIGITAL INTERFACE

A Digital Interface (DIF) Unit, which incorporates all of the functions to implement the Digital FCS configuration has been defined. A summary of the functions contained in the DIF is presented in Figure 99. As illustrated by Figures 86 and 96, the DIF is the system junction box which interconnects the system. This arrangement is convenient for purposes of conducting BIT and IFIM tests of all portions of this system.

4.6 MULTIPLEXING

The multiplexing analysis indicated that multiplexing of signals between the DIFs and the redundant sensors and actuators, was not necessary or desirable. Multiplexing between the display and flight management computers, as illustrated in Figure 96, was determined to be appropriate in order to provide flexibility. The recommended characteristics of the multiplexing system are summarized in Section 2.8.

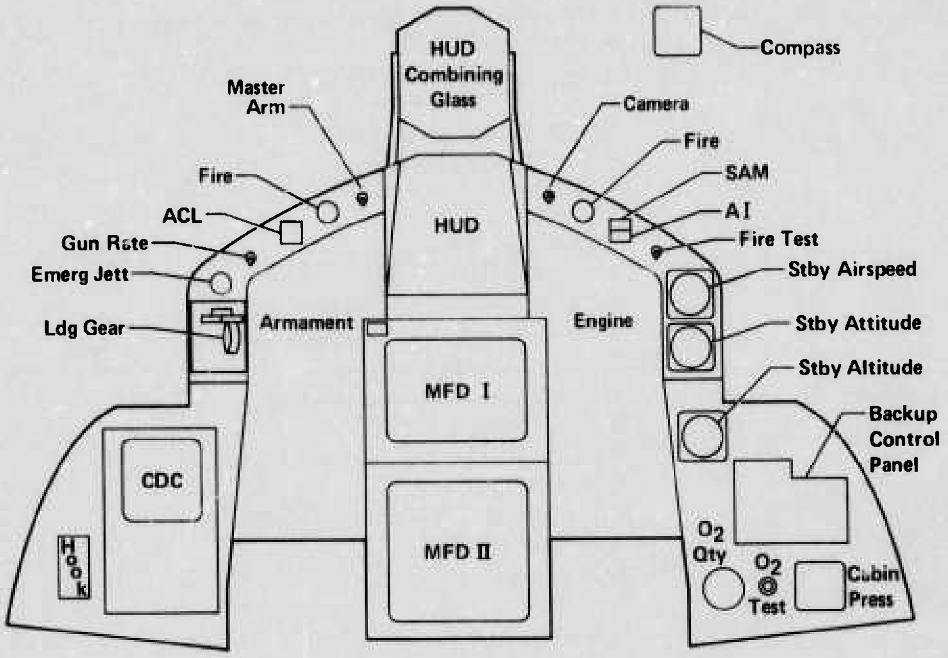


Figure 97
DFCS Forward Cockpit Display Arrangement

- The DFCS Displays will be Presented on Six Cathode Ray Tube (CRT) Devices as Follows:
  - Head-up Display (HUD),
  - Three Multifunction Displays (MFD I, MFD II, and MFD III), MFD I and II in the Forward Cockpit and MFD III in the Rear Cockpit, and
  - Two Computer and Display Controllers (CDC), one in Forward Cockpit and one in Rear Cockpit.
- Flight Control and Display Mode Selection may be Accomplished by Use of:
  - Appropriate Keys on the Forward or Rear Cockpit CDC,
  - Dedicated Switches on the Backup Control Panel, and
  - Dedicated Switches on the SSC and Throttles.
- Displays and Controllers-to-Flight Control Interfaces will be via MUX Bus(es) and Dedicated Wires.
- The Flight Control System Provides only Failure and Status Information to the Displays and Controllers.
- Area Navigation will be Provided Using TACAN and INS Information.
- Existing F-4 62-12200 Outer Loop Analog Sensors will be Used. A to D Conversion will be Performed in the Flight Management Computer.
- The F-15 Digital Computer (CP-1075/AYK) will be Used without Hardware Change and is Referred to as the Display Computer.
- The System uses, where Practical, Existing Proven Hardware, Software, and Interfaces.
- The System Provides a Full Complement of Displays and Controllers for Flight Control Mode Evaluation.
- The HUD will Provide Attack, Navigation, Situation, and Steering Information in Symbolic and Alphanumeric Formats.
- MFD I will Provide EADI and Essential Flight Information Redundant to that Provided on the HUD; and, in Addition, will Include Radar Displays and Provisions for TV-Format, Raster-Scan Presentations.
- MFD II will Provide, Simultaneously, Map Display, HSI Symbolic Display, Digital Parameters Associated with the Navigational Situation, and Threat Evaluation Data.
- MFD III will Provide Data Redundant to the Data Provided on MFD I.

Figure 98
Salient Features of the Displays and Controllers

(A) Power Supplies for Sensors and Controllers
- 28 VDC to ± 15 VDC
- 28 VDC to 13 VAC 1800 Hz
  28 VAC 400 Hz

(B) Analog to Digital Conversion
- Scaling and Buffering
- Parameter Sample and Hold
- A to D Converters

(C) Digital Data Transfer
- Data Storage
- Control Data Transfer - Direct Access
- Display Data Transfer - Multiplex Bus

(D) Digital to Analog Conversion
- Control Data Storage and Decoding
- D to A Converters

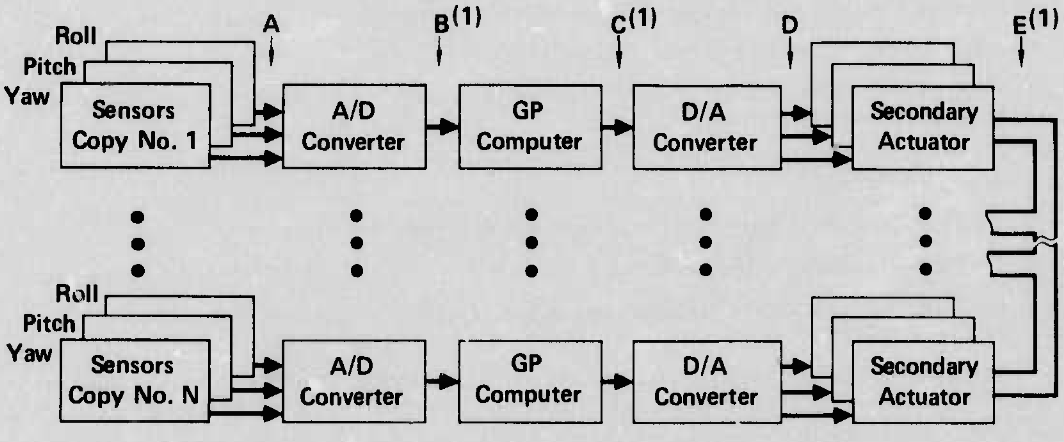
(E) Actuator Commands - Control Surfaces
- Servo Amplifiers
- Feedback Demodulators
- ΔP Demodulators

(F) Built-in-Test
- IFIM
- BIT Stimuli

Figure 99
Functions Contained in Digital Interface Unit (DIF)

4.7 FAULT RECOGNITION SCHEMES

The planned fault-recognition scheme will be implemented by a combination of cross-channel and in-line monitoring. It is planned that first faults will be detected using cross-channel monitoring at three voting planes as illustrated in Figure 100. It is planned that second faults will be detected by In-Line Monitoring for sensors, transducers and actuators and computer self-test summarized in Section 2.12.



(1)Voting Plane Locations

Figure 100
Cross-Channel Monitoring for the ADP

4.8 BIT AND IFIM

It is planned that a BIT scheme based on the top level flow diagram presented in Figure 39 will be implemented. The IFIM will be designed to provide fault coverage as indicated by Figure 47 wherein it is illustrated that the fault coverage required depends on the channel failure rate. The BIT will be designed to isolate failures to an LRU.

4.9 SOFTWARE MANAGEMENT PLAN AND COMPUTER MEMORY

A detailed software management plan was prepared as part of the Digital FCS Definition Study. It is planned that the Software Management Plan will be implemented in the ADP. The Development Cycle of the Operational Program is illustrated in Figure 101. The memory required for the display computer is given in Table 41. The memory required for the flight management computer is not available at this time. The memory required for each flight control computer is given in Table 42.

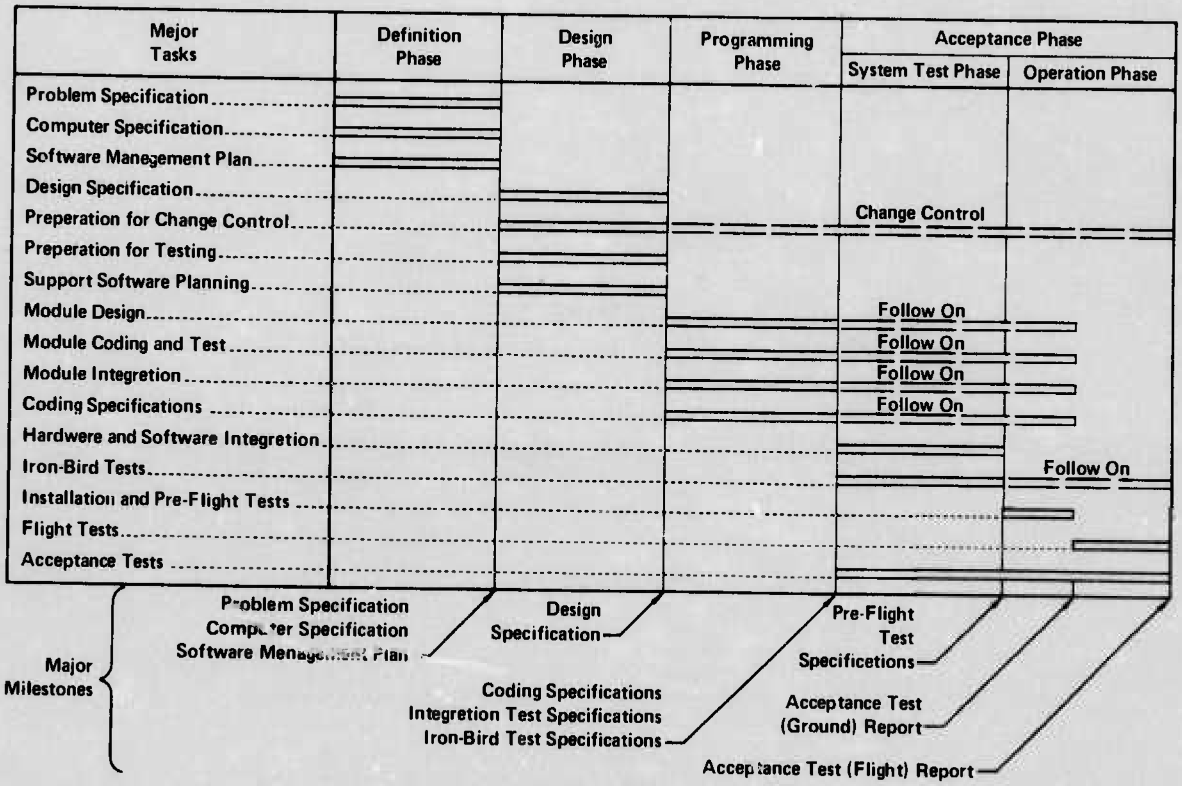


Figure 101
Operational Program Development Cycle
Software Development Phases

Table 41
Memory Requirements for Display Computer

Module	Memory Words (16 BITS)
Executive	840
Data Base	2,600
Subroutines	740
Self-Test	820
Navigation	2,960
Air-to-Ground	2,630
Air-to-Air	3,660
Flight Director	590
Controls and Displays	2,340
Radar Functions	7,000
Total	24,180

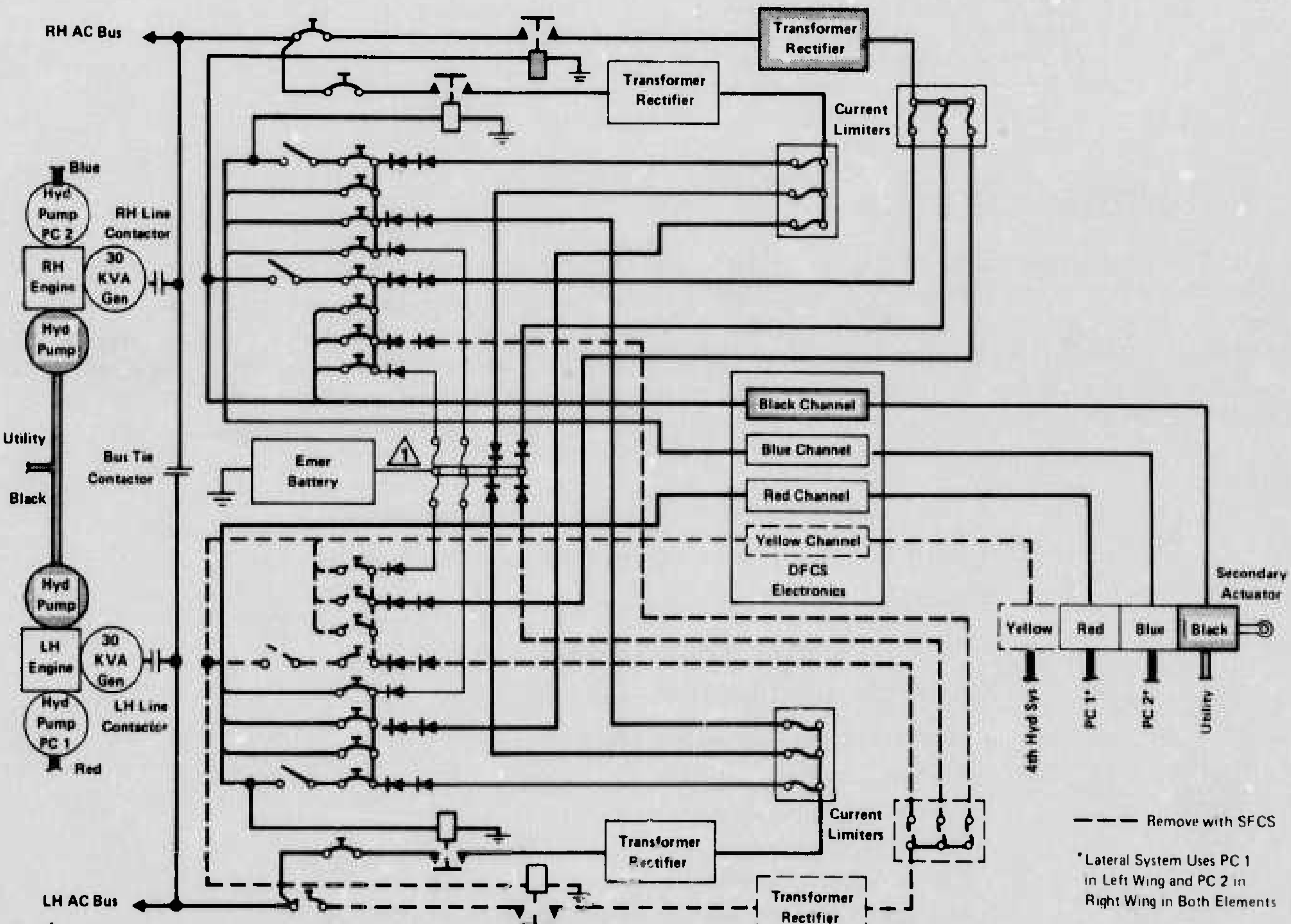
Table 42
Memory Required for Flight Control Computers

Function	Memory Triplex
Control Laws	4,750
BIT	2,000
Redundancy Management and/or IFIM	3,710
Executive	3,390
Total	13,850

4.10 ELECTRICAL SYSTEM

A simplified schematic of the planned Digital FCS electrical system is presented in Figure 102. Features of this arrangement include:

- o Each Digital FCS channel bus is supplied power from three sources:
  - o A dedicated channel Transformer-Rectifier (T/R),
  - o Crossfeed from one other channel T/R, and
  - o The SFCS and DFCS Essential Bus.
- o One emergency battery capable of backing up any or all channels.
- o All crossfeed circuits have diodes and limiters for fault-clearing and isolation.
- o The SFCS and DFCS Essential Bus is supplied by power from
  - o All channel T/Rs, and
  - o One battery.



*Lateral System Uses PC 1 in Left Wing and PC 2 in Right Wing in Both Elements

△1 SFCS and DFCS Essential Bus

Figure 102
Simplified DFCS Electrical System Schematic

4.11 CONTROL SURFACE IMPLEMENTATION

The control surface implementation which is planned to be used in the Digital FCS ADP is summarized in Table 43.

Table 43
Control Surface Implementation

Control Surfaces \ Motions	Pitch Rotation	Roll Rotation	Vertical Translation	Lateral Translation	Flat Turns	Yaw Rotation
Stabilator	U		U			
Rudder				U	U	U
Differential Ailerons and Spoilers		U		U	U	
Symmetrical Ailerons and Spoilers			U			
Differential Horizontal Canards				U	U	
Symmetrical Horizontal Canards	U		U			

U - Uses

4.12 LIGHTNING PROTECTION PLAN

The lightning protection plan for the ADP is summarized in Figure 103. The plan includes aircraft design and modification provisions intended to contain lightning on the surface of the aircraft; hardening of equipment to reduce susceptibility of equipment to transients induced by lightning current flowing on the surface of the aircraft; and a transient analysis lightning susceptibility test to evaluate the protective measures employed.

- **Install Lightning Arrestors on External Lights and Probes**
- **Install Bond Straps and Lightning Diverters in Nose Radome**
- **Install Bond Straps on Control Surfaces**
- **Install Lightning Arrestors on Electrical Power Buses**
- **Install Wiring per DFCS Guidelines**
- **Harden Marginal Equipment Circuits**
  - Bypass Capacitors
  - Metal Oxide Bypass Varistors
  - Transient Zeners
  - Series Resistor - Capacitor Combination
- **Conduct Lightning Susceptibility (Transient Analysis) Tests**

Figure 103
Lightning Protection Plan

4.13 ELECTROMAGNETIC COMPATIBILITY (EMC)

EMC techniques are presented in Section 2.10. A summary of the EMC considerations which are planned for implementation in the ADP are presented in Figure 104.

- **EMC Bonding Techniques**
  - MIL-B-5087B
  - MCAIR Process Specifications
- **EMI Generation and Susceptibility Control**
  - MIL-STD-461 Notice 3
  - MIL-STD-462 Notice 2
- **EMC Grounding Provisions**
  - Single Point Ground Concept
- **EMC Wire Processing Techniques**
  - Twisting
  - Separation
  - Shielding
  - Routing
- **Subsystem Interface Control**
  - Input and Output Characteristics
- **Control of Degrading Effects of Aircraft Environment**
  - Airframe Bonding to Provide Equipotential Ground Plane
- **EMC Verification**
  - Equipment EMC Tests
  - Aircraft EMC Ground Tests

Figure 104
Electromagnetic Compatibility (EMC) Summary

4.14 WEIGHT, SIZE, AND POWER

The estimated weight, size, and power of the principal components of the recommended Digital FCS is presented in Table 44. The general arrangement of the recommended ADP configuration is shown by Figure 105.

Table 44
Estimated Weight, Size, and Power of Digital FCS

Principal Component	Weight (lb)	Volume (cu in.)	Power (Watts)
Mechanisms	202	NE	NA
Wire	160	NE	NE
Actuators	451	NE	167
Hydraulics and Supports	259	NE	NA
Battery Installation	109	NE	NE
Electronics Except DIF	135	2,540	480
Digital Interface Unit	93	4,220	450
Panels	4	90	I
Controllers	79	2,100	253
Total*	1,492	8,950	1,350
Displays	119	3,618	900
Display Electronics	126	4,530	873
Total	1,737	17,098	3,123

* = Excluding Display and Their Associated Electronics
NA = Not Applicable
NE = Not Estimated
I = Included Elsewhere

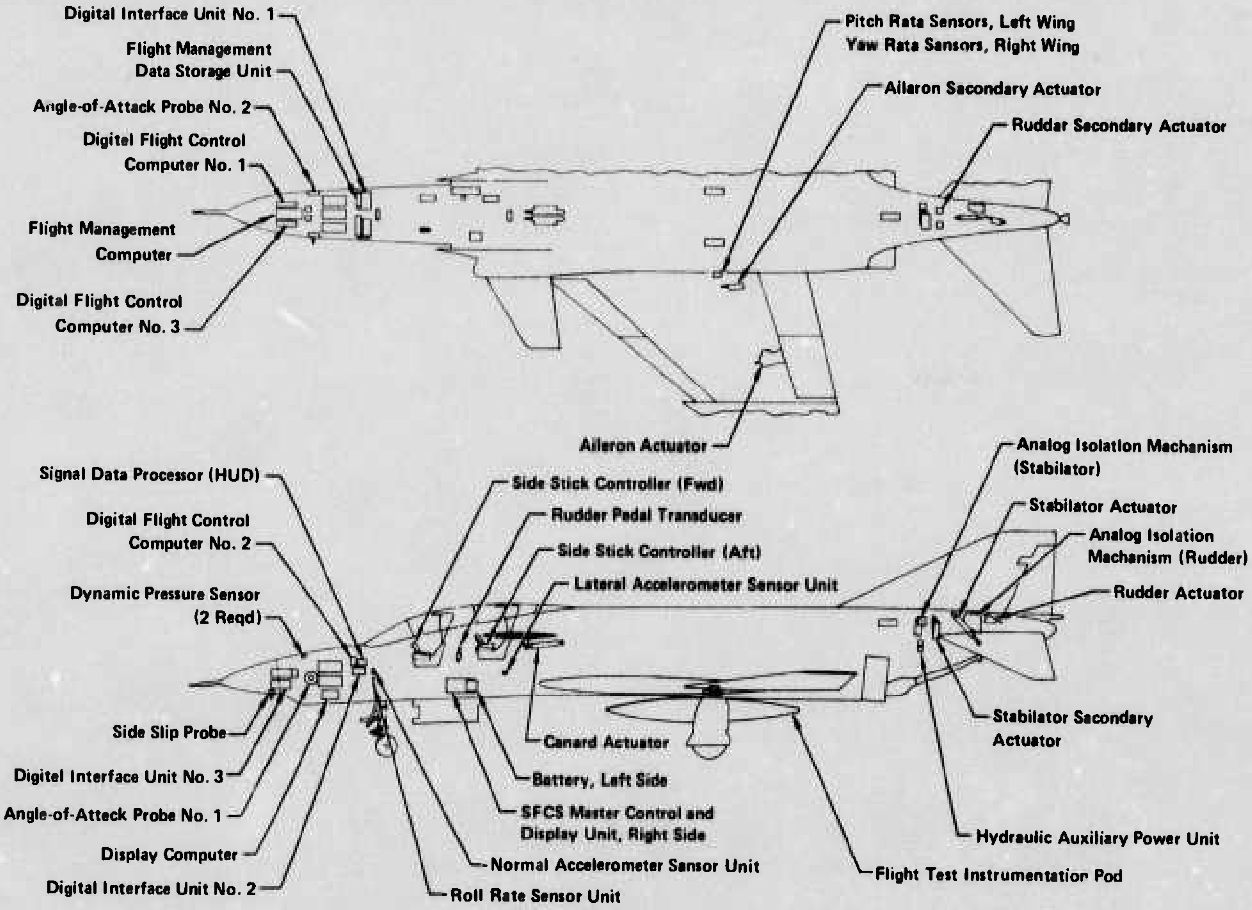


Figure 105
General Arrangement
Digital Flight Control System with Advanced Displays
Recommended ADP Configuration

4.15 SPARES, GROUND SUPPORT AND TEST EQUIPMENT

The concept for support of the Digital FCS recommended for the ADP is the same as the support concept used during the SFCS Program. The recommended support concept is summarized below.

4.15.1 F-4 COMMON (UNMODIFIED) EQUIPMENT - Unmodified F-4 equipment items will be requisitioned as needed to support the test aircraft. MCAIR has extensive records and experience with F-4 S/N 62-12200 and other F-4 aircraft used for testing purposes and can prepare estimates of required spares for use in establishing the minimum necessary stock of standard F-4 items.

4.15.2 F-4 MODIFIED EQUIPMENT - It is planned that certain F-4 equipment will be modified for use in the ADP. For example the F-4 Stabilator Actuator has been modified to provide rod-end load instrumentation and structural straps. To reduce delays due to failures of this type of equipment, it is recommended that one spare of each modified F-4 equipment item be obtained and stored as a spare.

4.15.3 DIGITAL FCS EQUIPMENT - It is planned that four flyable sets of all Digital FCS equipment be procured. This will provide one set for the aircraft, one set for the Iron Bird, one set for Flight Worthiness Tests and one spare set. It is not anticipated that any "bit and piece" spare parts will be procured and stored at the test site. Repair at the test site will be limited to LRU replacement and the failed LRUs will be returned to the supplier for repair as needed.

4.15.4 GROUND SUPPORT EQUIPMENT - A Mobile Ground Test Facility (MGTF), 24-foot highway trailer, was used to support the SFCS. It is planned that the MGTF will be modified by addition of special support equipment so that it can be used to support the Digital FCS in the same manner that it was used to support the SFCS.

It is not possible to prepare detail support equipment descriptions until the airborne equipment hardware detail design has proceeded to the point of a "design freeze", however, a list of ground support equipment which is recommended for the ADP has been prepared to aid in program planning and estimating.

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5.0 PROCUREMENT AND SUBCONTRACTING

5.1 GENERAL

Subcontracts were placed with General Electric, Collins, Honeywell and Lear Siegler to support MCAIR in the Analyses and Simulations associated with this program.

The summaries of the work accomplished, as reported in References (12), (15), (22), and (23) are presented on the following pages.

References:

12. Digital Flight Control System Study Final Report, ACS 10,713, General Electric Co., Binghamton, N.Y. October 1974.
15. Digital FCS Study Final Report, 523-0766085-00111M, Collins Avionics Division, Rockwell International, Cedar Rapids, Iowa. 15 February 1975.
22. Advanced Fighter Digital Flight Control System (DFCS) Definition Study - Final Report W0728-FR, Honeywell, Minneapolis, Minnesota. March 1975.
23. Advanced Fighter Digital Flight Control System Study - Final Report (Draft) ADR-789, Lear Siegler, Inc., Astronics Division, Santa Monica, California. April 1975.

5.2 SUMMARY OF REFERENCE (12) - TAKEN FROM G.E. REPORT

SUMMARY

The work described in this report was conducted in accordance with Purchase Order Z40018 of the McDonnell Douglas Corporation, St. Louis, Missouri (MCAIR). The project title is Digital Flight Control System Study. The study started April 1, 1974. The final report draft was submitted September 3, 1974, giving a study period of 22 weeks. The program concerns the application of digital flight control computers to fly-by-wire task and multimode flight control computations.

The MCAIR work statement lists six major tasks each of which is summarized.

MULTIMODE CONTROL DEVELOPMENT

The multimode control law development followed from work done for USAF Flight Dynamics Laboratory under two previous contracts. Control laws were synthesized for several control tasks: Air combat maneuvering (ACM), aerial gunnery, air to ground gunnery, and bombing. Included in the control law structure were angle-of-attack (α) and side slip (β) estimators. These provided α,β and $\dot{\beta}$ signals for the control laws. As a result the control law structure has the inherent ability to provide enhanced vehicle coordination and stable responsive control of high angle of attack. The ACM mode was programmed on the MCAIR simulation and integrated with the MCAIR developed control laws.

The angle of attack and side slip estimator and the air combat maneuver modes were further evaluated by programming these control laws on the General Electric MCP-703 triplex digital flight control computer and conducting a closed loop simulation. This was done in conjunction with the digital implementation of control laws task.

DIGITAL IMPLEMENTATION OF CONTROL LAWS

To study the digital implementation of control laws, including stability and dynamic performances of an airborne digital computer, a simulation program was written using the Xerox SIGMA 5 scientific computer. The computer simulation includes digital to analog (D/A) converters, analog to digital (A/D) converters and an analog simulation of the aircraft. This simulation was used to develop the filter mechanizations and other transfer functions used in flight control systems and to evaluate these in open and closed loop tests. Closed loop tests were conducted at 25, 50 and 100 iterations per second.

Closed loop operation was then undertaken with the General Electric MCP-703 triple digital flight control computer to verify simulated operation. Structural filter mechanizations were evaluated at 163 iterations per second with a filter notch of 141 radians per second. Closed loop operation with the MCP-703 triplex digital flight control computer demonstrated satisfactory performance of the structural filter mechanization and the air combat maneuver control laws developed in the multimode control development.

Fixed point mechanization of digital filters was directly addressed and resulted in development of three algorithms which cover the spectrum of filter precision requirements. Each is increasingly more complex but also more precise and it is not anticipated that flight control requirements will exceed the most precise algorithm. The structural filter was primarily used to evaluate the algorithms in closed loop, real time test using the MCP-703 system and verified predicted performance.

DATA REASONABLENESS

The data reasonableness task studied the application of the α and β estimators to the error testing of sensor inputs such as angle-of-attack, side slip and aircraft pitch, roll and yaw rates. The work included an error analysis of the angle-of-attack estimator. Data reasonableness tests of this sort offer significant advantages, by introducing signals from all redundant sensors to each estimator (via cross channel digital data transfer) the estimators have the capability to derive improved signal estimates. Data monitoring points are the estimator error feedbacks. An excessive error at that point triggers the removal of that error signal from the estimator computation while allowing further error monitoring to determine if the error represents a fault. In summary, this technique while still in its infancy offers an inherently simple and elegant technique for sensor fault monitoring, which may provide significant reductions in redundant system software and hardware devoted to the sensor monitoring and fault detection task.

IN-LINE MONITORING OF SENSORS AND ACTUATORS

The in-line monitoring of sensors and actuators task was conducted in three phases. First, the methods of in-line monitoring currently used or studied in past contracts were summarized. Secondly, other methods which are particularly suited to the digital flight control configuration under study were documented. The third part consisted of breadboard circuit design and evaluation of those methods which are particularly suited to the systems under study and for which test data was not available. The in-line monitoring applicable to the digital flight control are the following:

In-line monitor of LVDT's

In-line monitor of servoed accelerometer

In-Line monitor of rate gyro

Actuator monitoring

Design data on the LVDT monitor from the heavy lift helicopter direct electrical link program was included in the study. The in-line monitors for servoed accelerometers and rate gyros were designed, breadboarded and evaluated with their respective sensors. Applying in-line monitoring to the force summed secondary actuator required some cross channel data transfer. The failure detect logic for a triplex dual-fail-operational servoactuator is described.

COMPUTER RELIABILITY (MTBF), REDUNDANCY AND SELF-TEST

The computer reliability, redundancy and self-test task concerned itself with system configuration studies and evaluation of system test techniques. Three prime system configurations were studied.

Quadruplex Flight Control System with Dual Multimode Sensors

Quadruplex Flight Control Sensors and Secondary Actuators,
Triplex Computers and Dual Multimode Sensors

Triplex Flight Control System with Dual Multimode Sensors

The performance of a triplex, dual fail-operational system was evaluated in terms of the effectiveness of the computer self-monitoring function. A confidence factor was defined which expressed computer fault coverage as a probability determined by a failure rate proportion. A method for statistically estimating this confidence factor was developed. The use of statistical sampling techniques appears to be the only practical method for assessing the self-monitoring performance of complex digital systems.

REPORTS AND OTHER DATA

Monthly status reports were issued and a final report was prepared.

In summary, the work conducted will prove very helpful in selecting the best digital flight control system configuration for fly-by-wire and multimode control requirements.

5.3 SUMMARY OF REFERENCE (15) AND SIMULATION EFFORT BY COLLINS

Collins role in the DFCS study program provided a system concept and feasibility analysis for a Digital Flight Management System, these concepts were implemented and evaluated in the DFCS simulation.

The report addresses the philosophy for, the operation of, the benefits derived and problem areas of implementing a Digital Flight Management System in a modern or future fighter aircraft. The DFMS is essentially a "front-end" organizing system for a number of other major avionics systems. Included as candidate functions for integration and time-sharing of controller, display, and processor elements are: fully automatic navigation sensor management, sensor monitoring, unified horizontal situation display, electronic chart and threat display, automatic flight plan management and 3D steering outputs, mission and navigation data base management, fuel management aids, multi-function displays mode control, and some checklists and emergency procedures functions.

Those functions included as candidates for time-sharing display and/or controller elements but NOT processor elements are: multi-mode flight control, energy management, communications (digital and voice), IFF, AAI, multimode radar, electronic warfare and threat evaluation displays, and electro-optical sensors.

The DFMS complements the Multimode Flight Control System to give capabilities never before present in fighter avionics systems while at the same time reducing pilot workload, error probabilities, and required instrument panel areas. Particular subject areas included are pilot-computer communications, multi-sensor navigation, pilot workload analysis, software management, reliability analysis, candidate system architecture, and basic LRU definition with recommendations for a flight test evaluation.

Technology levels considered for basic LRU definition were those expected to be available in the 1976-1978 time frame. All other conceptual information remains valid for technologies expected in the 1980's.

Collins role in the DFCS simulation was to provide equipment, software, pilot training aids, and appropriate interfaces with MCAIR simulator and computers in support of a real-time dynamic simulation. The equipment provided included a Collins 8564B-2A computer, a modified 813H-1B computer and displays controller unit (CDC-1), a modified ACD-70 electronic chart system (for MFD-2 functions), and a flight data storage unit (8848D-2) for mass storage of basic computer programs, flight plans, navigation and steering programs, cartographic data, and control and display programs.

The major functions provided by Collins in the simulation included:

a. Digital flight control mode selection
b. Simulated automatic position fixing
c. 3D flight plan management and steering outputs
d. Moving map display and HSI
e. Emergency procedure display

The pilot interface to this equipment and functional description is presented in the pilot training materials included in the study report.

In summarizing this study report the following conclusions and recommendations are offered:

Conclusions:

a. A digital flight management system of the type described could be implemented with currently available, near state-of-the-art devices.

b. Pilot workload and procedural errors would be reduced considerably through the multisensor automatic navigation, subsystem management and control, and flight plan management concepts presented.

c. The use of this system would reduce considerably the panel area required and at the same time provide a considerable increase in the functional capability in the flight control, navigation, display, and subsystem management areas.

d. A dual system implemented as described provides mission completion information after one failure and aircraft survivability data after two failures. A rather unique capability of this concept is that in a single system failure condition, the pilot system interface rules remain constant, which is superior to the current method of having a different set of procedures for failure conditions.

Recommendations:

a. The systems to be managed by and their interface with the digital flight management system should be defined as soon as possible for the flight test program. This is a necessity as it must precede initial computer (speed, memory size) and external memory sizing.

b. A dual system installation as herein described must be seriously considered for the flight test program. There are significant questions in the areas of management functions assigned to dual systems and reversionary capabilities that can be answered only by flight test. Thus, the coordination of (partially) dual systems must be regarded as a major subject of concept validation program.

c. A reasonably accurate definition of all A/C subsystems to be managed by the digital flight management system will have to be made prior to the sizing of the computer and mass memory. The detail definition of CDC logic and display formats and major elements of MFD content can occur concurrently with the system development.

5.4 SUMMARY OF REFERENCE (22) - REPRINTED FROM HONEYWELL REPORT

INTRODUCTION AND SUMMARY

This report contains the results of investigations conducted in several technology areas which are important to a digital fly-by-wire flight control system development. This work was done in support of a McDonnell Douglas Corporation (MCAIR) study program -- "Advanced Fighter Digital Flight Control System, Definition Study (Digital FCS Study)." The report is organized into seven sections, plus supporting appendices. The sections are briefly summarized below.

- Section 1 - Redundancy and Reliability Concept Investigation -- A tradeoff study of six candidate redundancy configurations applicable to a digital flight control system (DFCS) is presented. The configurations were supplied by MCAIR. In addition, a detailed investigation is made of numerous technical issues associated with the derivation of a redundancy management scheme. Based on the tradeoff study and the detailed redundancy evaluations, a baseline configuration is defined and recommended for the DFCS. This configuration is a simple, triplex digital system with a computer-to-computer data exchange transmission as the only link between redundant channels. Finally, the feasibility of a dissimilar backup channel is examined, with emphasis being placed on fluidic technology as a potential approach to add reliability and provide lightning and radiation immunity.

- Section 2 - Data Reasonableness Concept Investigation -- Several approaches to single-channel fault detection/isolation using data reasonableness testing are discussed. This type of testing is applied as an alternate to adding redundant sensors for fault detection. The general conclusion reached is that this type of testing will be applied only for specific, unique requirements.

- Section 3 - In-Line Monitoring Concept Investigation -- In-line monitoring techniques applicable to a redundant DFCS are described. These techniques are especially important to a triplex DFCS, such as the baseline configuration, in that they provide much of the self-test capability required to achieve acceptable flight reliability levels. All of the in-line monitoring concepts discussed would be used in such a DFCS mechanization.

- Section 4 - Energy Management Development and Implementation -- An energy management autopilot control loop is developed and analyzed. Performance results are presented for the F4E aircraft with candards. Acceptable intercept and path following performance is obtained with the developed control laws.

  The computer requirements for on-line generation of energy management profiles are also estimated. The computer load is sufficient that integration with the DFCS computer is not feasible.

- Section 5 - Digital Implementation of Control Laws -- With Honeywell's HDC-301A processor selected as the nominal DFCS computer, sizing estimates are made for the DFCS control laws provided by MCAIR. In addition, using Honeywell's DIGIKON software, the control laws are analyzed for iteration rate, word length, and digitization effects on performance. This analysis provides the basis for the computer parameter selections that are made and recommended.

  A technical discussion of control law digitization design considerations and an approach to modularizing the control software are also included in this section.

- Section 6 - Pilot/Computer Communications -- The hardware requirements for several different displays configurations are defined. The information that is to be presented by this hardware on a head-up display (HUD) and two multifunction displays (MFDs) was provided by MCAIR. The configurations include use of redundant display drives and use of different data transmission interfaces with the DFCS mechanization.

  Software sizing estimates required for the display information are also made.

- Section 7 - Software Development -- The various aspects of developing and using safe flight software are discussed in detail in this section. Included are techniques for verifying the flight software, support hardware and software, software configuration and change control, and an estimate of a realistic development schedule.

  It is concluded that the verification and control requirements must begin with a proper software structure, which uses modular techniques, followed by a rigorous set of test procedures to debug the software. Change control is exercised on the computer product end item (i.e., airborne computer tape and/or software listing) in much the same manner as control over hardware has been accomplished in the past.

DFCS SOFTWARE SIZING SUMMARY

An overall software sizing estimate of the DFCS system, excluding displays, is shown in Table 0-1. These summary data are based on the control function software sizing done in Section 5, the redundancy management estimates of Section 1, the in-line monitoring requirements of Section 3, and projections of executive functions (e.g., mode logic and initialization) from the experience gained on the A7 Digital Multimode and JA37 DFCS programs. Based on the baseline configuration, requirements for the DFCS are 159,200 operations per second of computational time and 8217 words of memory. This is well within the capability of the selected Honeywell HDC-301A computer, which has a speed capacity of 217,000 operations per second computational time using the instruction mix identified in Section 5. It can also interface with 16,000 words of memory, which is the software complement assumed for the redundancy tradeoffs of Section 1.

Table 0-1. DFCS Sizing Estimate - Baseline Configuration

Parameter	Computation Time				Memory	
	Mul/Sec	Add-Load/Sec	I/O/Sec	Total	Instructions	Data
Control laws	9960	63,000	4520	77,480	3259	1410
Sensor processing	---	12,600	1980	14,580	400	184
In-line monitoring	960	33,080	3200	37,240	485	95
Actuator monitoring	---	12,160	1280	13,340	222	48
Mode logic	---	9600	1200	10,800	536	54
Noncritical S.P.	---	4800	960	5760	102	72
Initialization	---	---	---	---	100	10
Preflight BIT	---	---	---	---	1200	40
Total	10,920	135,240	13,140	159,200	6304	1913
Percent of Total	6.85	84.9	8.25	100	---	---

5.5 SUMMARY OF REFERENCE (23) - REPRINTED FROM LEAR SIEGLER REPORT

STUDY SUMMARY

Flight control requirements have become increasingly complex in modern aircraft with ever increasing growth in the computational requirements for which more components are needed. This in turn causes an increase in the size and a corresponding decrease in the reliability of conventional analog flight control computers.

In order to overcome this problem, the use of digital computation has been explored by both industry and government laboratories. As a result, the feasibility of utilizing digital computation for automatic flight control has been established through several hardware developments and experimental flight test programs. As a result of many analytical and hardware studies, Astronics developed a digital computer specifically for flight control. The result of this effort is the ASTRO-1601 central processing unit and associated input/output and control and display units all of which have been built and tested.

The advanced fighter digital flight control system study reported here was based upon the previous and current experience and consisted of evaluation of the configuration concepts applicable to the advanced fighter flight control problem and demonstrating these concepts with hardware in the laboratory. The study was organized around four major areas, namely, establishment of a digital flight control system redundancy management concept, examination of synchronous versus asynchronous computer operation, development of digital computer self test routines and a redundant hardware laboratory demonstration.

The redundancy management concept was developed around the selection of a system configuration from various alternates. A system configuration baseline was established consisting of a variety of input redundancy levels to satisfy the various fail operative requirements. For example the sensors involved in the two fail-op modes are defined as quadruplex in the baseline while sensors required for single fail-op are triplex. In order to maintain the integrity of the quadruplex sensors, four input processors are utilized. The digital computers defined for the study are based upon the ASTRO-1601 microprogrammed processors. With the use of high confidence in-line monitoring capability, the computers can achieve two fail-op capability with only three units, therefore the baseline is defined with triplex computers. The actuators are assumed to have a high in line monitoring capability and therefore are defined as triplex.

In order to answer several issues that have arisen with respect to the use of synchronous or asynchronous operation, a study was conducted involving the simulation of a triple redundant computer configuration on an IBM 370 general purpose computer facility. The purpose of the simulation was to examine input accuracy and bias effects, independent sampling/computation rates, high input signal rates, and integrator divergence.

In the study of the trade-offs between synchronous and asynchronous operation, those factors which would appear to be differences between the two operations are discussed. The main points answered are the benefits which are offered in either approach, the mechanization differences, the operational differences and the reliability differences. This study verifies that asynchronous operation provides more reliability when employed in redundant digital flight control systems through the avoidance of the potential single point failures of synchronized clock operation. It also avoids the necessity to develop and qualify redundant hardware clocks or to develop and validate the software logic for a software clock. This will result in lower program costs for the asynchronous approach. Another benefit of asynchronous operation is the reduction in EMI induced control surface transients. This results from the fact that there is a low probability of all channels being in the same computation cycle at the time the EMI effect is present. The subsequent output signal selection will eliminate the single channel transient.

Redundant computer operation has been demonstrated in the laboratory using two complete channels of digital computing hardware. In addition, the redundancy management concepts of input signal selection, command signal selection, integrator equalization and failure detection and switching have been demonstrated as well as the inherent asynchronous operation. An extensive software self test has been prepared and partially demonstrated but the extent to which it can detect all digital computer failures has not been determined. The demonstration program utilizes 1360 words of memory and the timing utilization of the demonstration program is 32% plus self test.

Self-test requirements for the DFCS computer are satisfied by providing monitoring and test features for each function of the computer. The power supply is checked by comparison of output voltages with independent references and current level monitors. The CPU is checked by using a watch dog monitor and a comprehensive self-check of the microprogram using software routines, and checking for illegal combinations. The servo loop is checked by using wrap-around checks, and sample inputs. Since most of these techniques are in common usage, this study concentrated on the area that is unique to the Astronics mechanization, namely the self test aspects of the ASTRO-1601 and in particular the software routines which can provide a high level of self test capability without the burden of additional dedicated self-test hardware. A software self test program was developed which performs the following tests. Every instruction is tested at least once. Every instruction addressing mode is exercised at least once. Every possible path in the microcode is exercised. Where possible, identity relations are employed and the test data is changed at each iteration.

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