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INTEGRATED AIRFRAME/PROPULSION CONTROL SYSTEM ARCHITECTURES (IAPSA) STUDY*

Christopher M. Carlin
Boeing Military Airplane Company
and
Alan D. Stern
Allied Bendix Flight Systems Division

Abstract

The purpose of the IAPSA study was to define, evaluate, and select candidate aircraft control system (ACS) architectures for 1990's high performance airplanes. An airplane possessing a high degree of airframe/propulsion coupling was selected as the application aircraft and ACS architectures were developed using two approaches. The first approach developed a baseline state-of-the-art system that preserved much of the autonomy of traditional flight and propulsion control subsystems. The second was a top-down "integration from the start" approach which was not constrained by tradition and which employed suitable emerging technologies.

Tne selected architecture, called "central/direct", has the following features: 1) a highly redundant centralized computer complex in which all control processing is performed; and 2) all electronics reside in two similar (fail-operative) dispersed boxes that are optically connected in a direct manner to sensors and servovalves.

Introduction

This paper reports the first phase of a multiphased research and technology program planned to: 1) investigate the benefits that integrated control system architectures may have upon the reliability/cost tradeoff of airframe/propulsion control systems for future high performance aircraft, 2) develop and build a representation of the most promising architectural candidate for validation in the Avionics Integration Research Laboratory (AIRLAB), and 3) if deemed necessary, conduct flight tests.

The emphasis of the study was the cost-effective enhancement of future airframe/propulsion control systems in the areas of reliability, maintainability, availability, system flexibility, and life-cycle cost (LCC). The IAPSA study accomplished the objectives summarized below:

a) Investigated the benefits and reliability/cost tradeoffs for integrating the propulsion control system (PCS) with the airframe flight control system (FCS);

b) Examined emerging technologies and their suitability or limitations for application in 1990's integrated architectures;

c) Based on cost/benefit considerations, selected a generic advanced (1990's) Aircraft Control System (ACS) architecture applicable to a high performance supersonic aircraft with a high degree of propulsion/airframe coupling, and performed a preliminary design of this ACS; and

d) Defined experiments, costs, and schedules for validating the selected integrated architecture in NASA Langley's AIRLAB.

This paper reports significant results pertinent to objectives a), b), and c).

System Requirements Definition

An advanced 1990's high performance fighter aircraft with highly coupled flight and propulsive controls was postulated. This aircraft featuring canards, flaperons, 2-D vectoring nozzles, a mixed compression inlet, and an advanced turbojet engine presents a multivariable coupled control design problem. Integration design requirements were formulated. In addition, the required probability of mission success and aircraft loss were defined and substantiated for the integrated ACS architecture.

Survey and Evaluate Technology

Several emerging technologies were identified as having potential impact on the integrated ACS architecture. These include: distributed computer networks, VLSI and VHSIC microcircuits, fault-tolerant computers and software, optical circuits, fiber-optic communications, analytic redundancy, high temperature electronics, digital actuators and sensors, system validation methods, and contention buses. The current and projected state of the art (SOA) has been assessed for these technologies as well as their implications for future integrated ACS's.

Architecture Development

Two classes of integrated ACS architectures were developed for comparison. The first (baseline) is a bottom-up approach to integrating the PCS and FCS functions using current SOA technology. This baseline assumes an autonomous PCS and FCS which are then integrated. The FCS is based upon the AFTI/F-16* (Reference 1); and PCS upon the Bendix developed system for the ATEGG

*Contract performed by Boeing Military Airplane Company for NASA/Langley Research Center, No. NAS1-16942, February 1982. Bendix Flight Systems Division was subcontractor.

*USAF/Navy/General Dynamics/Bendix Advanced Fighter Technology Integration using the F-16 as a demonstrator.

program** as well as the F401 FADEC program*** (Reference 2). The inlet control is based upon NASA/Boeing SCR (Supersonic Cruise Research) studies (Reference 3).

The second class of architecture (alternates) was developed using a top-down design whereby functional partitioning was unconstrained by traditional boundaries, and emerging technologies are employed as appropriate. A wide range of alternate architectures were evaluated against each other and the baseline, so as to measure relative reliability, maintainability, cost, etc. These were then narrowed down to two alternate architectures for further consideration. One of these two alternate architectures was selected for more detailed design, evaluation, and ultimate development and demonstration. Criteria for this selection are given.

Systems Requirements and Scope

The IAPSA architecture development was deliberately restricted in scope to the flight and propulsion control functions. Included in the analysis were shared sensors normally included in the non-flight critical avionics system but supportive of the control function (e.g., air data, inertial reference system). The architecture was extended to the control effectors through the actuator electronics and servovalves but not including the power actuators and secondary power.

Although the IAPSA study was intended to develop generic system architectures, a representative aircraft was required to form the basis for system development. An advanced tactical high altitude supersonic (M=2.5) penetrator was used (Figure 1). Its mission and characteristics are listed as follows:

Mission

a) 4 hour ferry mission
b) Supersonic penetration mission
 - -0.15 hour to FEBA
 - -0.30 hour supercruise ingress
 - -0.30 hour supercruise egress
 - -0.15 hour FEBA to land
c) STOL landing

Characteristics

a) Mixed compression inlet
b) Twin engines
c) Close-coupled canards
d) 2-D vectored thrust nozzles (required for STOL)
e) Trailing edge flaperons
f) Rudder

Airplane characteristics offered an opportunity for multivariable blended control effector usage such that several control alternatives were possible. This is shown in Figure 2. Normal pitch, roll, and yaw control was via the canards, flaperons, and rudder respectively. STOL and full "g" maneuverability required the use of the 2-D nozzles on each engine. Under unfailed conditions level 1 flying qualities and full mission capability were achieved in the above manner. A full range of effector failure conditions are postulated in Figure 2. Reconfigurable control strategies were formulated to support both flight safety and mission functions. These reconfiguration strategies, along with relaxed static stability, imposed a requirement for a fully fly-by-wire augmented ACS. A similar approach was followed relative to the propulsion control function (Figure 3).

The ACS implemented traditional FCS and PCS functions as well as several integrated control functions. These included:

FCS Requirements

- o Command and stability augmentation (CAS)
- o Control effector blending and limiting
- o Manual control modes and STOL
- o Autopilot modes: altitude, heading, airspeed hold/select
- o Guidance modes: lateral/vertical navigation, autoland
- o Flight envelope limiting

PCS Requirements

- o Inlet control

Landing/Subsonic	-Lock surfaces at maximum area
Transonic	-Maintain best thrust-drag
$1.2 \le M \le 1.6$	-Position shock at lip
$M > 1.6$	-Maintain throat Mach, position normal shock aft of throat

- o Engine Control
  - Provide thrust proportional to request
  - Prevent speed, temperature, pressure exceedances
  - Maintain inlet/engine airflow stability margin
  - Control engine accelerations and decelerations

Integrated System Aspects

- o Control effector blending
- o Computer/sensor/bus sharing
- o Automatic test
- o Analytic redundancy
- o Control functions
  - Subsonic: Airframe Mach sets inlet mode
  - Transonic: Airframe Mach sets inlet mode and engine airflow limits
    - Air data basis for inlet analytic redundancy
    - Inlet data basis for engine analytic redundancy
    - Flight path commands and air data used to maintain inlet/engine airflow stability margin
  - All Conditions: Autothrottle via FADEC
    - Thrust vector control via FADEC

**Advanced Technology Engine Gas Generator program by Pratt & Whitney and Allison

***Full Authority Digital Electronic Control program by the Navy, Pratt & Whitney and Hamilton-Standard

One of the contract tasks was to establish design requirements for flight safety reliability and mission abort rates in the 1990 time frame. (The ACS was considered essential to *flight safety and the mission.* The 4-hour ferry mission was considered the pacing flight safety design requirement. The supersonic penetration mission was used to measure the ACS mission reliability. Both engines were required for supersonic flight.) First, an overall airplane loss rate was established based upon historical trends. Figure 4 illustrates the loss rate trend (Reference 4) for both single and twin engine fighters. Based on these data a loss rate of 4 (per 100,000 hours) was used for IAPSA. Next, the portion of the loss rate due to the combined FCS/PCS function was required. This was approached from several points of view: historical (Reference 4), aircraft cost sensitivity, and expected potential systems capability. The *historical* data are shown below. In all but the F-16 case the data base reflects aircraft losses due to FCS electronics.

Airplane	Loss Rates* (all sources)	Loss Rate* (control system)	Ratio
F-14	12.4	0.5	0.04
F-5	11.0 @ 200,000 hrs	no breakout	
F-111	9.9	no breakout	
F-15	6.3	0.43	0.07
F-16	13.0 @ 92,000 hrs	3.0 FCS 1.0 PCS 4.0 ACS	0.31
MIL-F-9490D	10.0	0.5 excluding secondary power	0.05

*Per 100,000 hours and a data base of at least 500,000 hours (except as noted).

From an aircraft cost perspective, it is pertinent to examine the sensitivity of total aircraft buy to ACS-induced loss rate. Figure 5 presents the total number of aircraft purchased as a function of total loss rate. As shown, 500 *airplanes are required to support a loss rate of* 4 per 100,000 flight hours according to the operational scenario listed.

If we assume that control electronics account for 10% of the total loss rate (0.4), a total of 7 aircraft could be saved if the ACS never failed. Therefore, there is not a large procurement advantage in attempting to improve loss rate to better than the historical value of 0.5×10^{-5}.

Finally, the AFTI/F-16 program has a FCS reliability design goal of 1×10^{-7}. This is certainly achievable, and is worthwhile provided that the cost of achieving it is not too high. *The flight safety reliability goal for IAPSA was* placed at 5×10^{-6} for the combined PCS/FCS integrated ACS.

Mission success probability (MSP) requirements were also established. The combat mission was examined by looking at completed sorties versus fleet sortie cycles for various combat loss rates (Figure 6). Loss rates due to equipment failures were superimposed. The results show that equipment-induced loss rates would have to exceed 1,000 per 100,000 sorties to have a significant effect on the combat MSP. This would yield a $P_{Abort} \leq 10^{-2}$ for all causes. If, as has historically been true, 10% of these are due to the ACS function, the ACS-caused MSP should be $P_{Abort} \leq 10^{-3}$. This value is consistent with MIL-F-9490D and the F-15A, and was used for IAPSA.

Baseline (BL) Architecture Development

A baseline SOA integrated IAPSA architecture was developed to provide a reference against which alternate architectures utilizing emerging technologies were compared. Ground rules for the BL system included: 1) autonomous initial SOA designs of the PCS and FCS; 2) provision for functional and hardware integration of these initially autonomous PCS and FCS architectures; and 3) use of an hierarchical MIL-STD-1553B bus structure. The architecture formulated was based upon the AFTI/F-16 FCS and the PCS from the FAFTEEC contracts* (Reference 5). This architecture is shown in Figure 7. Features of the BL are as follows:

- o The ACS shares air data and inertial reference system (IRS) sensors that interface to the avionics bus.
- o The avionics bus is interfaced *independently* to redundant propulsion and flight control computers.
- o The IRS provides flight safety inertial sensing to the FCS and, as such, has a direct interface to the flight control computers since the avionics bus is not safety critical. Flight safety required impact pressure, static pressure, and angle-of-attack sensors are interfaced separately to the flight control computers independent of the air data computer.
- o The PCS and FCS have a dedicated flight safety interface independent of their *common connections over the avionics bus.*

Reliability and life-cycle-cost (LCC) analyses were conducted on the BL. Minimum equipment lists (MEL) were developed to support the flight safety and penetration missions. From the MELs, success logic diagrams were developed for each function as a basis from which to launch the reliability analysis. Figure 8 is the success logic diagram for the flight safety actuation function which is based upon the results of Figure 2. The diagram shows that the rudder is the critical link and must be extremely reliable. Also shown are the multiplicity of alternate control strategies for the canard, flaperons, convergent nozzle (C/N), and thrust vectored flap (V/F). *Diagrams such as Figure 8*

*Full Authority Fault-Tolerant Electronic Engine Control-Two AFWAL /POTC contracts with Bendix/Detroit Diesel Allison, and Pratt & Whitney Hamilton-Standard were linked together for each functional ingredient of a particular mission. These were then analyzed using the Stage-State reliability analysis technique (Reference 6). Component mean-time-between-failure (MTBF) and failurecoverage probabilities were taken from the AFTI/F-16 and FAFTEEC data bases. These programs were considered the 1982 baseline data base which was extrapolated to 1987 for meaningful architectural comparisons. Examples of significant changes between the two data base periods are listed below.

Item	MTBF Changes (hours)
Computers	4K to 20K
Actuator Servo-valves	6.7K to 20K
Fuel Metering Valves (24)	3.6K to 11.5K
Hydraulic Engine Valves (38)	51K to 91K
Engine Pressure Sensors (16)	8K to 26K

Item	Coverage Change
Actuator Servo-Valves	0.95 to 0.99
Sensors	0.97 to 0.99
Fuel and Hydraulic Components	0.95 to 0.99

The reliability impact of transitioning between the two data bases was evaluated for the BL system as shown below.

	Probability of	
	Airplane Loss	Abort
IAPSA Requirement	5×10^{-6}	10^{-3}
1982 Data Base	6.09×10^{-5}*	7.18×10^{-4}
1987 Data Base	4.21×10^{-6}	2.44×10^{-4}

*Exceeds requirement

The differences are mainly attributable to the actuator servo-valve. This is shown in Figures 9A and 9B where the three architectures are compared using the 1987 data base. The probability of aircraft loss is dominated by the rudder servo reliability, and the probability of abort is dominated by PCS (engine, inlet, nozzles) mechanical components. This is true to the degree that electronic control system architectural reliability trades are virtually masked. Figure 8 illustrated this criticality for the rudder. The PCS mechanical components become critical for mission abort due to the requirement for two-engine operation to support the mission, combined with the requirement for 18 servovalves per engine. The $P_{ABORT} = 2.44 \times 10^{-4}$ includes dual PCS actuation since the IAPSA requirement cannot be met with simplex actuation ($P_{ABORT} = 1.34 \times 10^{-3}$).

The IAPSA study did not perform an actuation design, rather, a reasonable approach was postulated to assure realism. Results do indicate the importance of good actuation functional reliability. The IAPSA program emphasized the electronics architecture trades, and reliability results associated with those trades were developed.

Alternate Architecture Development

Advanced 1990s ACSs were developed using a top-down integration design approach employing emerging technologies as appropriate. The technologies examined, their availability, and their impact on the ACS are listed in Figure 10. This information is based on an industry/government survey. Most of the technologies that strongly impact the integrated architecture will be available in the mid-1980s. One significant exception is high temperature electronics (HTE). HTE can be a strong enabling technology for fully distributed electronic architectures allowing functionally beneficial placement of electronics on the engine, and at the control surface actuators for supersonic airplanes where local temperature can be high. A summary of HTE and other emerging technology architectural impacts is as follows:

1) Distributed Computer Networks - Fundamental alternative to centralized computing. Allows distributed intelligence, parallel processing, and reduced communications bandwidth (and wires) for fault detection, isolation and reconfiguration (FDIR).

2) Fault-Tolerant Computers - Provides ultra-reliable core for central processing. Combined with VLSI/VHSIC, provides the ability to reduce the number of independent computers in the system without sacrificing necessary reliability or throughput.

3) Fiber Optic Communication and Optical Sensors/Actuators - Allows optical interface to sensors and actuators. Allows most (if not all) electronics to reside in an environmentally protected central core. Provides for reduced EMI/EMP sensitivity.

4) High Temperature Electronics - Allows distribution of electronics to hot areas. For the IAPSA aircraft, this is a necessary technology for localized (distributed) computing unless several conditioned environment areas are distributed throughout the aircraft.

5) Contention (masterless) Buses - Eliminates the need for a master bus controller, and the associated need within a redundantly-configured ACS for reliably designating the processor responsible for master bus control.

6) VLSI/VHSIC - Provides throughput in a single processor necessary for centralized processing of the integrated aircraft control function.

Several (6) advanced IAPSA potential architectures were identified. After initial evaluation of these, two fundamentally different advanced architecture approaches were selected and analyzed in-depth. These are:

- Distributed/Distributed (D/D) - This name refers to distributed parallel processing and distributed physical location of electronics with serial multiplexed buses providing interconnectivity throughout the airplane.

- Centralized/Direct (C/D) - This ACS has centralized computer processing. That is, any one of the multiple redundant computing elements in the centralized electronics complex can perform the full set of controls processing. Direct optical connections are provided between sensors/actuators and two centrally located boxes containing all system electronics.

The D/D ACS was based upon three emerging technologies: VLSI/VHSIC, HTE, and high speed buses. The C/D system combines VLSI/VHSIC, power-by-light, optical multiplexing, optical sensors, fault-tolerant computing, and software validation technologies.

Two versions of the D/D ACS were examined as shown in Figure 11. Version "A" uses a fault-tolerant highly redundant and reliable central bus controller. This controller directs message traffic, monitors the health of the bus and correctness of transmissions, and reconfigures about detected faults. Version "B" avoids this central bus control function, since such a function: 1) presents a quasi "single-point" failure mode that limits system reliability, and 2) imposes a synchronous communication constraint that is incompatible with loosely coupled asynchronous elements. Instead, each element on the bus can autonomously access the bus with proper prioritization and fault protection. This bus is masterless and is typical of existing masterless protocols such as "token passing" and CSMA/CD (Reference 7). The features of the D/D approach are:

1) Asynchronous system operation

2) Frame synchronous redundant computer operation

3) Redundant bus operates active/standby/

4) Sensor/actuator fault detection, isolation and reconfiguration (FDIR) performed locally

5) Canard/flaperon/rudder controllers also provide the minimum CAS function necessary for level III flying qualities

6) Analytic redundancy for inlet and engine sensors using shared air data

The C/D architecture is shown in Figure 12. This architecture centralizes all control electronics into two boxes for survivability. However, from a redundancy management perspective both boxes act as a unit. Each box is independently fail-operative, and jointly the boxes are <u>at least</u> two-fail operative for flight safety functions. Sensors and actuators are optically interfaced to the ACS boxes. A survey of optical technology (discussed later) revealed that a full complement of optically driven pressure, position, rate, and acceleration sensors, and actuator drives will be possible by 1990 - perhaps much sooner with adequate development effort. This permits all ACS electronics to be centrally located and protected.

The internals of each box consist of several optical interfaces and computing elements (CE) interconnected by a redundant serial multiplexed I/O bus (Figure 13). There are three CE's in each box, each of which performs all the propulsion and flight control processing. (Projected improved capability in computing power in VHSIC technology makes this approach quite feasible.) One of each set of dual redundant engine sensors interfaces to each box. The boxes are also cross-strapped via redundant serial data links. The I/O sampling is asynchronous to the CE's and runs at hardware speeds. The CE's are frame synchronous and the two boxes function as one for redundancy management purposes. For example, there are a total of six CE's; with majority voting, CE FDIR can sustain four CE losses and still be fully operational.

<u>Analysis of Alternative Architectures</u>

The D/D architecture reliability was expected to show improvements relative to the BL as summarized below.

	Change from BL	Reliability Effect
1)	Increased number of computer stages	Decrease
2)	Increased amount of cross-strapping on input/output stages	Increase
3)	Air data and inertial calculation change from duplex to triplex	Increase
4)	Analytic redundancy applied to achieve engine sensor success with any 4 of 7 engine sensors	Increase Increase
5)	Improved MTBF of computers	Increase
6)	Improved actuator servovalve MTBF	Increase

A detailed stage-state reliability analysis of this D/D architecture was conducted. The "electronics only" probability of aircraft loss for the D/D system, (without a bus controller) compared to the BL, improved from 1.24 x 10^{-7} per hour to 0.375 x 10^{-7} for the FCS function; and including the PCS function, from 1.30 x 10^{-7} to 0.628 x 10^{-7} per hour. The effect of computer MTBF on the D/D architecture reliability is of interest since it has twenty-nine distributed microprocessors. This is done in Figure 14 for electronics only and with varying data bases relative to 1982 for both versions "A" and "B" of the D/D system. The BL comparison uses a 1982 data base. One observation is that a central bus controller (version "A") limits and dominates reliability even if it has a 10 million hour MTBF for the bus control function. Secondly, improvements in reliability due to computer MTBF's higher than 20,000 hours are not significant. Finally, average (i.e., system) improvements in MTBF and coverage can realistically improve reliability over the next ten years by an order of magnitude.

The C/D system presented some new and difficult reliability analysis challenges. This is due to multiple levels of dependencies combined with the M out of N analytic redundancy associated with the engine sensor function. Two key levels of dependencies exist. The first is the optical interfaces which are shared by several sensors.

In the case of the dual engine sensors a separate interface in each box is used for each set. The second dependency level consists of the serial interfaces between boxes. These dependencies along with analytic redundancy provided 472 success states for the engine sensor function. A special extension to the Stage-State reliability analysis methodology had to be formulated to systematically generate these success states (Reference 8). A survey of existing reliability analysis tools revealed that no current tool could analyze such a system.

Reliability comparisons of the BL, D/D version B, and C/D architectures with similar data bases and without actuation (i.e., electronics only) are shown in Figures 9A and 9B to be:

Flight-Safety Reliability, P (per hour)

BL	D/D-B	C/D
1.3×10^{-7}	0.628×10^{-7}	0.0575×10^{-7}

Probability of Abort, P (per hour)

BL	D/D-B	C/D
4.85×10^{-5}	3.98×10^{-5}	1.25×10^{-5}

Other comparison considerations are also important. Availability is strongly related to reliability and also to the need for maintenance. One possible measure of this is to compare the mean time to first failure (MTTFF). Here the C/D architecture stands out inasmuch as its sensors are passive optical devices and it has considerably fewer line replaceable units (LRUs) than the D/D and BL systems. The MTTFF's compare as follows: BL = 100 hours; D/D = 150 hours; and C/D = 600 hours. Another measure is the capability to perform multiple sorties without maintenance: BL = 16 sorties, D/D = 20 sorties, and C/D = 77 sorties before mission reliability diminishes below $P_{Abort} = 10^{-3}$. These results are for electronics only, since actuation otherwise dominates and masks system differences.

Life-cycle-cost (LCC) comparisons were made based upon 500 aircraft flying 300 hours/year for 15 years. Basing included three squadrons per base, twenty-four aircraft per squadron and six operational bases. Fifteen year life cycle costs compare as shown in Figure 15. The C/D system again is best primarily due to the reduced number of computers.

An examination of maintainability revealed that major payoffs were not found in architecture variability. Rather, these payoffs relate to specific hardware/software design and proper system installation. Factors affecting maintainability consist of accessibility, self-sufficiency, power plant modularization and condition monitoring, use of automatic test, device built-in-test (BIT) and rapid high coverage FDIR. The C/D system probably is superior in terms of accessibility due to its few and centrally located electronics units; otherwise all the architectures are equal in this respect.

Architecture Selection Summary

Major conclusions regarding each system are discussed below followed by a qualitative comparative analysis. The assessment of the BL system is as follows:

- FCS sensors are dedicated by channel thus limiting reliability
- Only limited FCS/PCS integration is provided, especially in terms of requiring dedicated hardware rather than shared resources
- The digital buses are not safety critical requiring the provision of separate flight safe backup links
- Its LCC is comparatively high

Version "A" of the D/D system was rejected in favor of version "B" due to reliability limitations and synchronous communication constraints. Version "B" of the D/D system is characterized by:

- Increased connectivity relative to the BL providing increased system flexibility and reliability
- No FCS/PCS distinction is made and hardware is shared where appropriate
- Analytic redundancy is used to increase reliability and reduce sensor count
- Inefficient use of system resources (large number of LRUs) results in higher LCC and shorter mean time between unscheduled removals relative to the C/D system
- Increased electrical power and environmental control system complexity

The C/D architecture is described as being:

- A highly integrated system
- Most mission-available with lowest cost and reduced sparing requirements due to fewer LRU's
- Better suited to tightly coupled high bandwidth integrated control laws due to single computer operation
- Easier to provide environmental control
- Simplified electrical power distribution and power supply/battery support
- Most immune to EMI/EMP threats
- Unconstrained by localized high temperature effects
- Less efficient with increasing aircraft size due to the direct connections of centralized electronics with sensor and actuators
- Higher risk with greatest payoff

The above criteria are summarized in Figure 16 in a relative sense. The BL is considered the reference with the D/D and C/D systems compared. As shown, the C/D is the selected system based upon a 1990 technology availability date. The key to the C/D system is the availability of optical technology. A preliminary optical design of the C/D system is presented below.

Optical Design

The optical design began with a review of current literature to identify candidate sensor technologies. Potential sensors are listed in Figure 17. These sensors are either established technology (position and rate), or have been demonstrated in the laboratory. No fundamental problems are foreseen in the development of any of them.

Using the candidate sensors, a preliminary fiber count was made assuming that no optical multiplexing was used. That system required 186 fibers per box. The ability to provide connectors for 186 fibers on an ATR sized package is a problem. Therefore, the system was redesigned to use optical multiplexing where feasible, resulting in a 50% reduction in fibers. The pressure and temperature multiplexing scheme is shown in Figure 18 for a representative interface. The position, discrete, and servo multiplexing scheme is typical, where signals having slightly different wavelengths are combined on a single fiber connected to a particular location where they are split into separate fibers connected to individual sensors. A typical multiplexing scheme is shown in Figure 19 for the inlet and control surfaces. In all cases, care was taken not to degrade reliability when introducing multiplexing.

Finally, layouts were designed for the pressure and position sensor interface cards (Figures 20 and 21). These were chosen as being representative. The control elements are mechanized using large scale gate arrays. Chip carrier packaging is used to increase circuit density. Electrical package sizes are based on JEDEC standard chip carriers. Optical component sizes are based on existing devices with allowances for the use of integrated optics. Each of the 2 electronics boxes is expected to include 25 card slots and have dimensions of approximately 11" x 10" x 20".

Summary

Three integrated airframe/propulsion control system (ACS) architectures were developed. The baseline (BL) was a state-of-the-art (SOA) design that integrated autonomous PCS and FCS systems. Two alternate 1990's ACS's were developed in a top-down integrated sense from the start. These alternates employed emerging technologies and were compared against each other and the BL. Two widely differing alternates were examined--one using parallel distributed (functional and physical) processing (designated D/D), the other centralizing the processing into two centrally located redundant electronics complexes (designated C/D). The C/D system located all redundant computing elements and interfacing electronics in two boxes with optical sensor and actuation devices connected optically to the two boxes. Evaluation revealed the C/D architecture to be better than the other two in 5 of 10 categories. This compared to the D/D which did so in only 2 of the 10 categories. One area of concern for the C/D system was the SOA of optical devices. A preliminary design revealed that the technology should be well in hand to support a 1990 technology availability date for aircraft application.

References

1. Ramage, J. K. and Watson, J. H.; "AFTI/F-16 Digital Flight Control System Preliminary Development", presented at the National Aerospace and Electronics Conference (NAECON), Dayton, Ohio, May 20-22, 1980

2. Lenox, T. G., et. al., United Technologies Corp., Pratt & Whitney Aircraft, West Palm Beach, FLA., "Full Authority Digital Electronic Control-Phase 1", Report No. FR-8652A, June 1978, Naval Air Propulsion Center, Trenton, NJ

3. Boeing Commercial Airplane Co., Seattle, WA., "Advanced Concept Studies for Supersonic Vehicles", NASA Contractor Report 165771, October 1981, NASA Langley Research Center, Hampton, VA

4. AFR173-13, "USAF Cost and Planning Factors"

5. Detroit Diesel Allison Division of General Motors, Indianapolis, Ind., "Full Authority Fault-Tolerant Electronic Engine Control System for Variable Cycle Engines", AFWAL-TR-82-2037, June 1982, Aero Propulsion Laboratory, Wright-Patterson AFB, Ohio

6. Stern, Alan D., Boeing Military Airplane Co., Seattle, WA., "Stage-State Reliability Analysis Technique", Paper No. 20, presented at AGARD Avionics Symposium, June 22-26, 1981, Roros, Norway

7. IEEE 802 Local Network Standard, IEEE Computer Standards Committee, July 1981 (draft)

8. Chen, Hai-Chow; Boeing Company, Seattle, WA., "A Generalized Stage-State Method for Centralized Fault-Tolerant Flight Control Systems", to be presented at the AIAA Guidance and Control Conference Paper No. 83-2301-CP, August 15-17, 1983, Gatlinburg, Tenn.

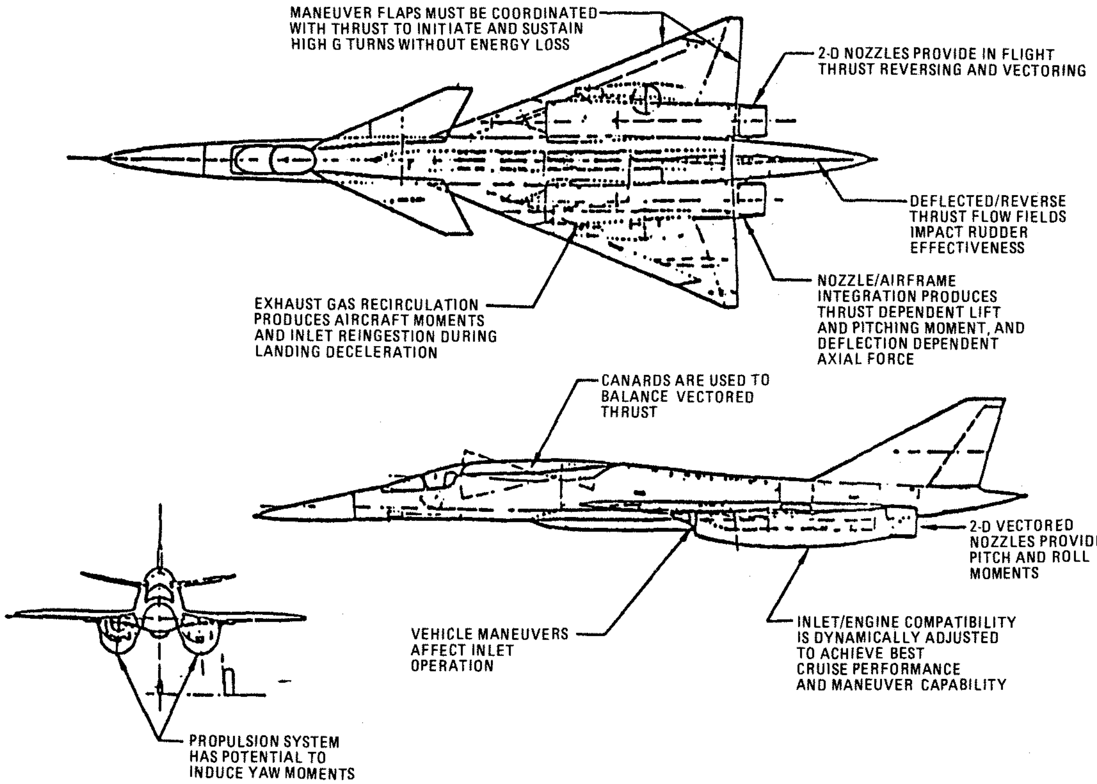

Figure 1. IAPSA Aircraft with Integrated Controls

Control effector options/functions							Flying quality level	Procedure		Comments
C_L	C_R	F_L	F_R	N_L	N_R	RUD		Cont'd mission	Return to base	
P	P	R	R	Stol IM	Stol IM	Y	R 1 P 1 Y 1	2.5 g turn 4.0 g evasive √		Normal mode (2,000 ft ground roll) Stol only if all control systems operative
X(1)	P	PR	PR	P	P	Y	R 1 P 2 Y 1			3.0 g capability (limited evasion)
X(1)	X(1)	PR	PR	P	P	Y	R 1 P 3 Y 1		√ (2)	2.5 g capability (limited evasion) Limited descent corridor
X(1)	X(1)	PR	PR	X	PR	Y	R 2 P 3 Y 1		√ (3)	1.7 g capability Limited descent corridor
X(1)	X(1)	PR	PR	X	X	Y	R 3 P 3 Y 1		√ (4)	1.5 g capability Limited descent corridor
P	P	X	R	R	R	Y	R 3 P 1 Y 1	√ (2)		Marginal mission
P	P	X	X	R	R	Y	R 3 P 1 Y 1		√	1.5 g capability Very limited low altitude roll capability Limited descent corridor
P	P	R	R	Y (5)	Y(5)	X	R 1 P 1 Y 3	√ (2)		Can perform normal mission except for large thrust asymmetry and crosswind

Nomenclature:

Configuration:
- C_L C_R Left and right canard
- F_L F_R Left and right flaperon
- M_L M_R Left and right thrust nozzle (thrust for 1 g)
- RUD Rudder

Function:
- IM Instantaneous maneuvering
- P Pitch function
- R Roll function
- STOL Stol lift
- Y Yaw function
- X Now operative

Notes:
- (1) Non-operative canard floated
- (2) Degraded mission
- (3) Required 3000 ft ground roll
- (4) Requires 4300 ft ground roll
- (5) Yaw trim—may be too slow for satisfactory control

▭ Revised 6-19-82

Figure 2. Aerodynamic Control Effector Options

Control effector options/functions										Operational mode
ENG_L	ENG_R	INL_L	INL_R	A/B_L	A/B_R	C/N_L	C/N_R	V/F_L	V/F_R	
O	O	X	X	X	X	O	O	O	O	Short field approach (length < 2000 ft)
O	O	X	X	X	X	O	O	X	X	Conventional field approach (length > 2000 ft)
O	O	X	X	O	O	O	O	O	O	Short field takeoff (length < 2000 ft)
O	O	X	X	O	O	O	O	X	X	Conventional field takeoff (length > 2000 ft)
O	O	X	X	X	X	O	O	X	X	Subsonic cruise
O	O	O	O	O	O	O	O	X	X	Transonic maneuver
O	O	O	O	O	O	O	O	O	O	Transonic acceleration
O	O	O	O	X	X	O	O	X	X	Supersonic cruise
O	O	O	O	O	O	O	O	O	O	Supersonic maneuver

Nomenclature:
ENG_L, ENG_R left and right engine
INL_L, INL_R left and right inlet
A/B_L, A/B_R left and right afterburner
C/N_L, C/N_R left and right convergent nozzle
V/F_L, V/F_R left and right vectored nozzle

Function:
Basic thrust
Supersonic operation
Thrust augmentation
Optimal engine operation
Thrust vectoring

Legend:
O Operative
X Non-operative

Figure 3. Propulsion System Options Sustain Flight Requirements

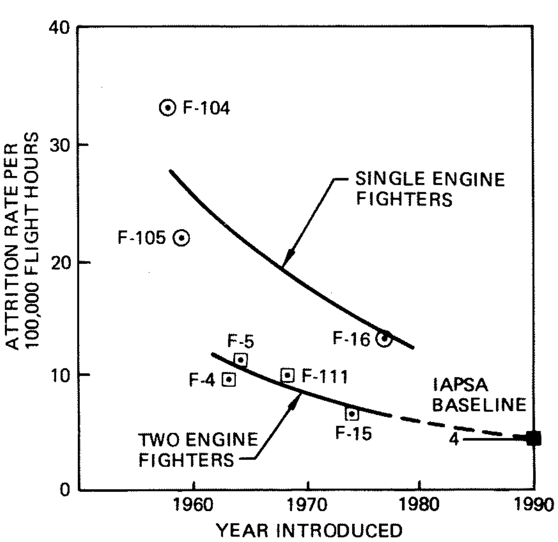

Figure 4. Attrition Prediction Used in LCC Analysis

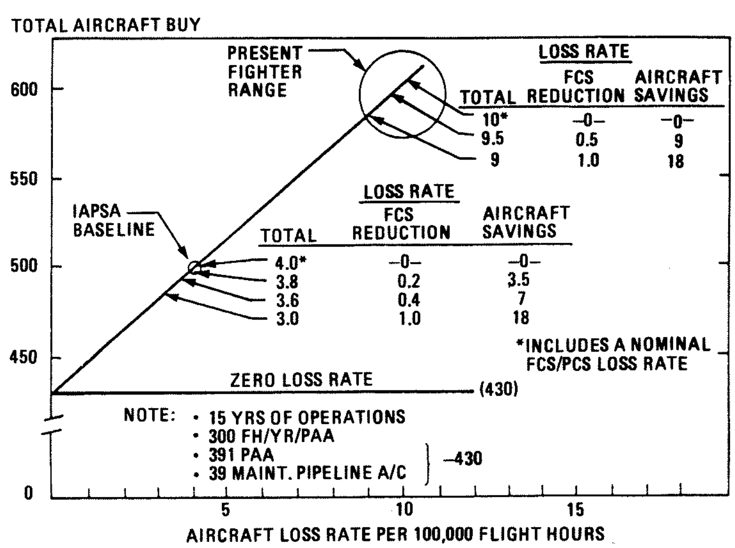

Figure 5. Sensitivity of Aircraft Buy to Changes in Control System Loss Rates

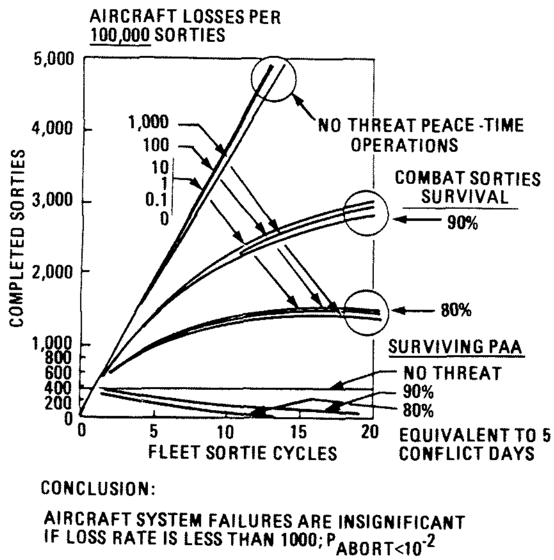

Figure 6. Relative Effect of Threat Induced Losses

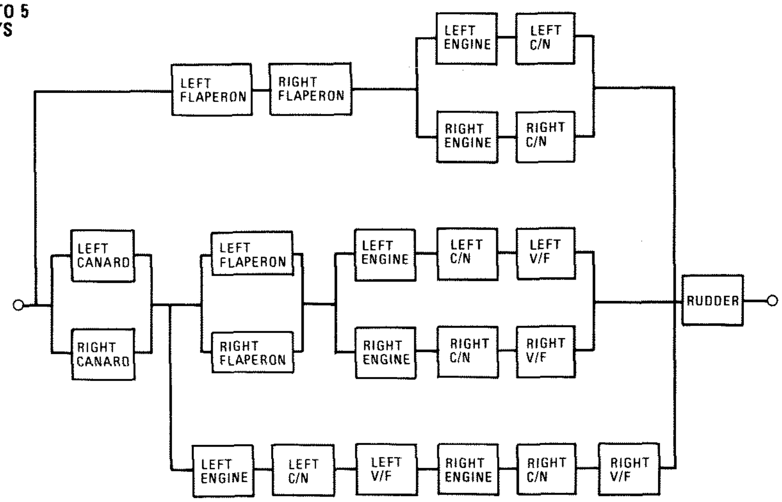

Figure 8. Success Logic for Flight Safety Actuation

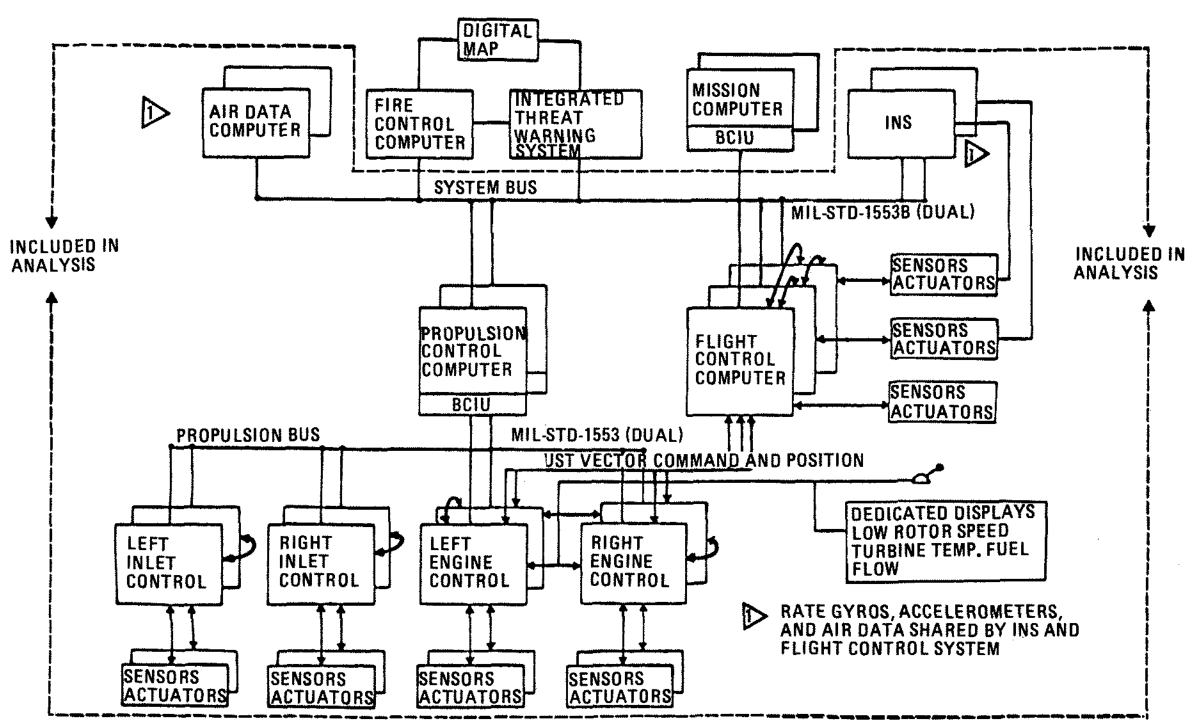

Figure 7. IAPSA Baseline Architecture

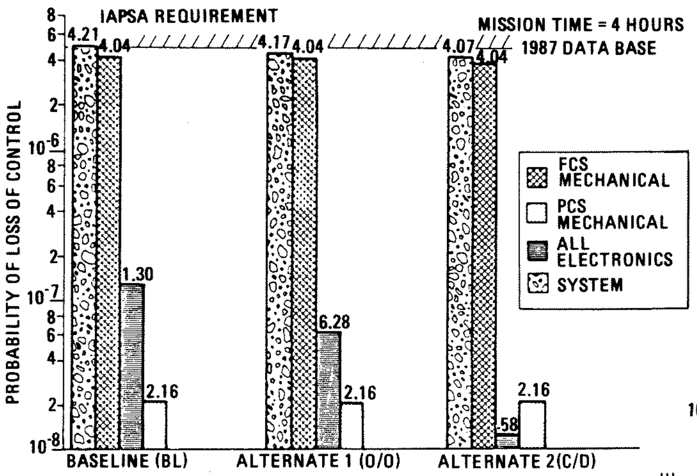

Figure 9A. Reliability Comparison--Flight Safety Reliability

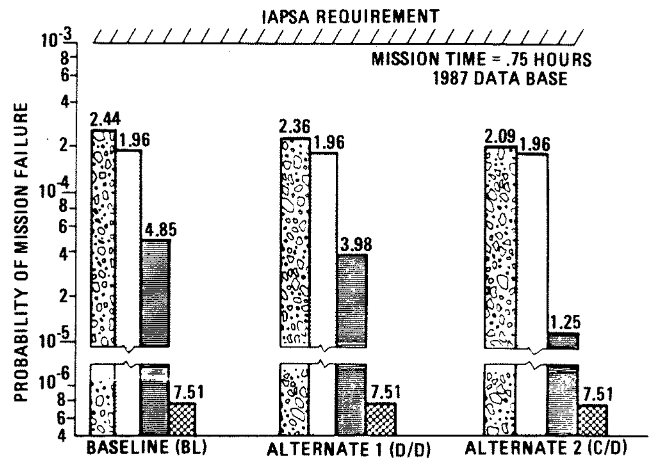

Figure 9B. Reliability Comparison—Mission Reliability

Technology	Availability		Significant impact				
	1985	1990	Architecture	LCC	Performance	Reliability	Integration impact
Distributed computer networks	X	X	X		X		X
VLSI/VHSIC microcircuits	X	X		X	X	X	X
Fault tolerant computers	X	X	X	[2]		X	X
Fault tolerant software		X		[3]		X	
Optical circuits		X	[4]		[1]		[1]
Fibre optic data communication	X	X	X		X	X	
Analytical redundancy	X	X		X		X	X
High temperature electronics		X	X	[3]		[3]	
Digital actuators		X	X				
Digital sensors	X	X	X				
Contention buses	X	X	X		X		X
System validation methods	X	X		X		X	

[1] Significant effect but likely to be surpassed by VHSIC
[2] Through scheduled maintenance
[3] Potentially adverse impact
[4] VLSI electro optic interface

Figure 10. Emerging Technology Impact Summary

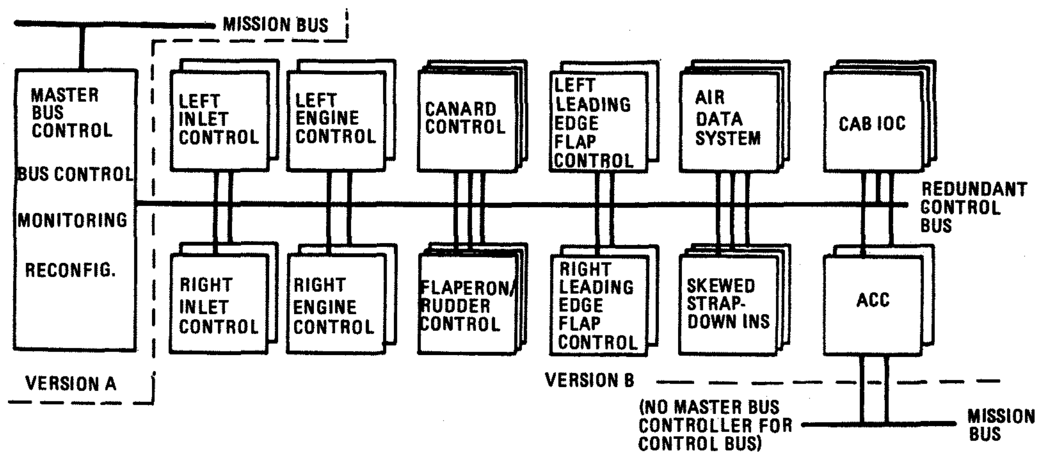

Figure 11. Direct/Distributed Architectures (D/D)

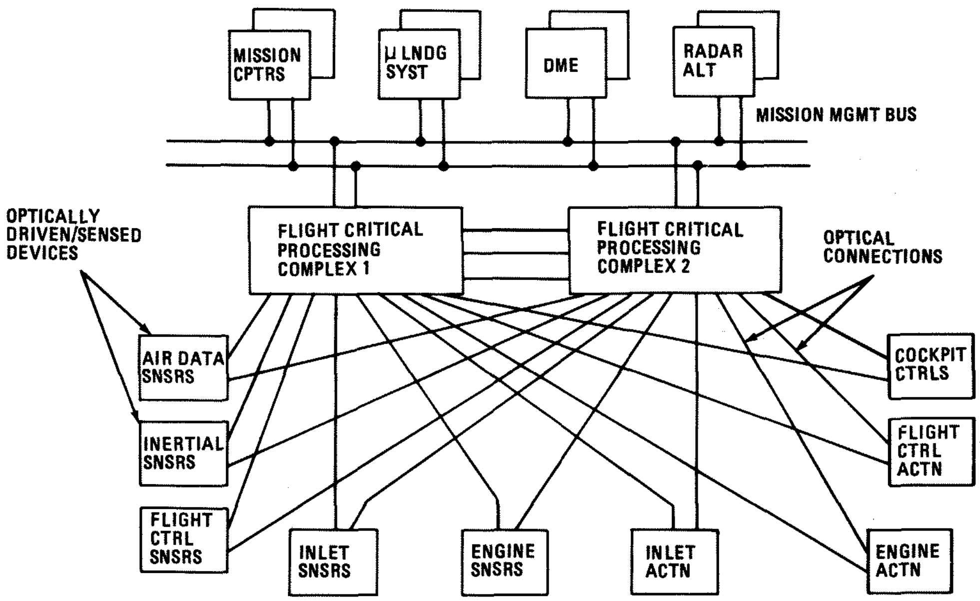

Figure 12. Centralized/Direct (C/D) Architecture

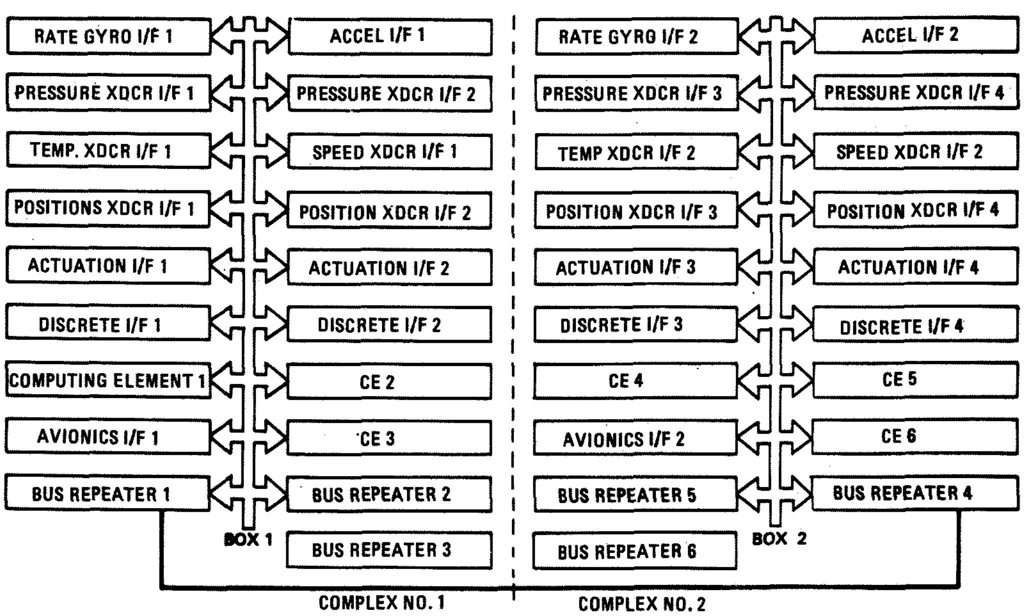

Figure 13. C/D Dual Electronics Boxes

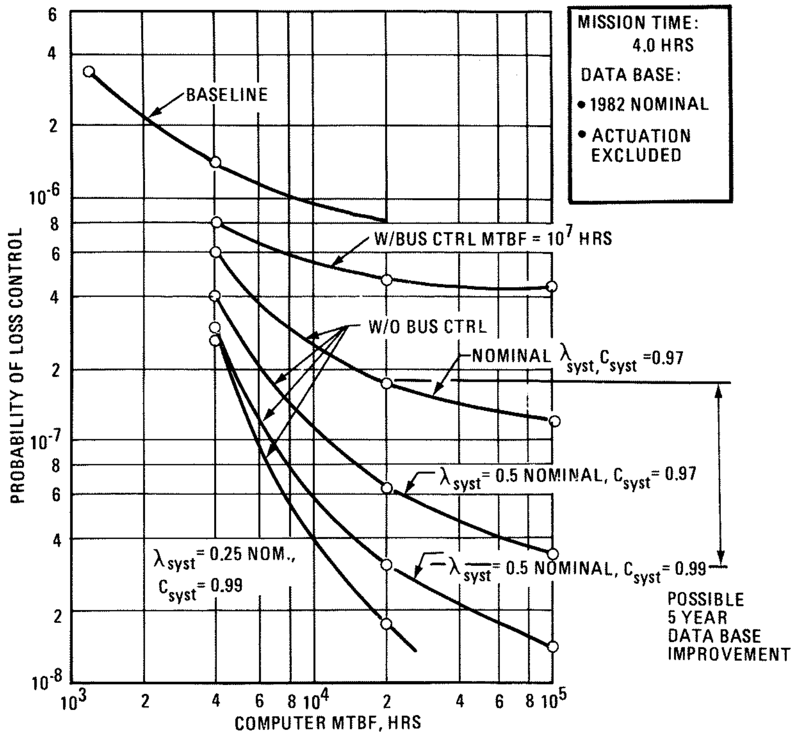

Figure 14. D/D Architecture Flight Safety Reliability Trades

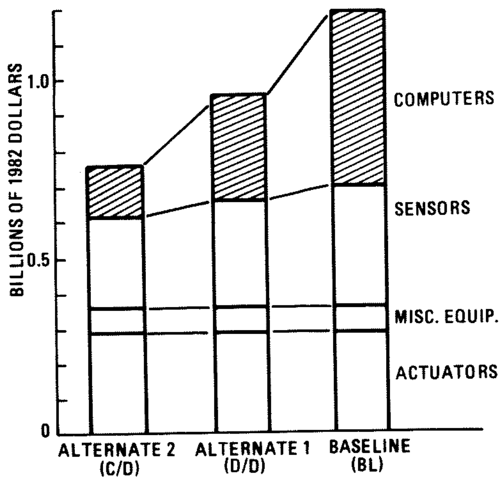

Figure 15. IAPSA 15 Year Life Cycle Costs

	BL	D/D version B	C/D
Reliability	Good	+1 better	+2 best
Maintainability	Good	-1 worst	+1 best
Availability	Good	+1 better	+2 best
Life-cycle cost	High	+1 medium	+2 low
Flexibility	Low	+2 high	+1 medium
Computing requirements	Low	0 low	-1 moderate
Environmental control and electrical power complexity	Moderate	-1 high	+1 low
Survivability	Medium	0 medium	+1 best
EMI/EMP immunity	Good	+1 better	+2 best
1990 technical rist	Low	0 low	-1 medium
	0	+4	+10 Selected

Figure 16. Architecture Evaluation Matrix

Pressure:
1. Microbend
2. Interferometer
3. Photoelastic

Temperature:
1. Selective absorbtion in No-yag or EU-glass
2. Broadband interferometer

Acceleration:
SAGNAC interferometer

Position:
Encoded plate with TDM

RPM:
Pulse counter

Discrete outputs:
Ga As- FET photoswitch

Servo-drives:
PWM GaAs-FET photoswitch

Figure 17. Candidate Sensor Technologies

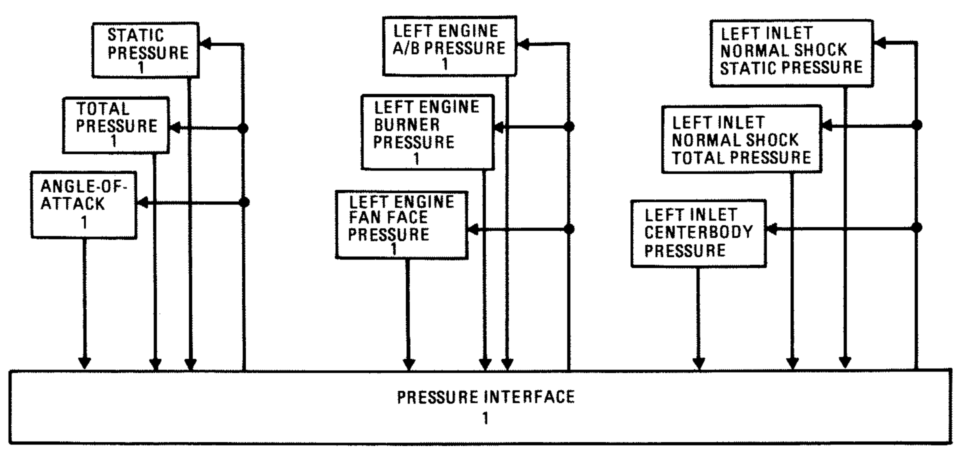

Figure 18. Pressure Sensor Interface

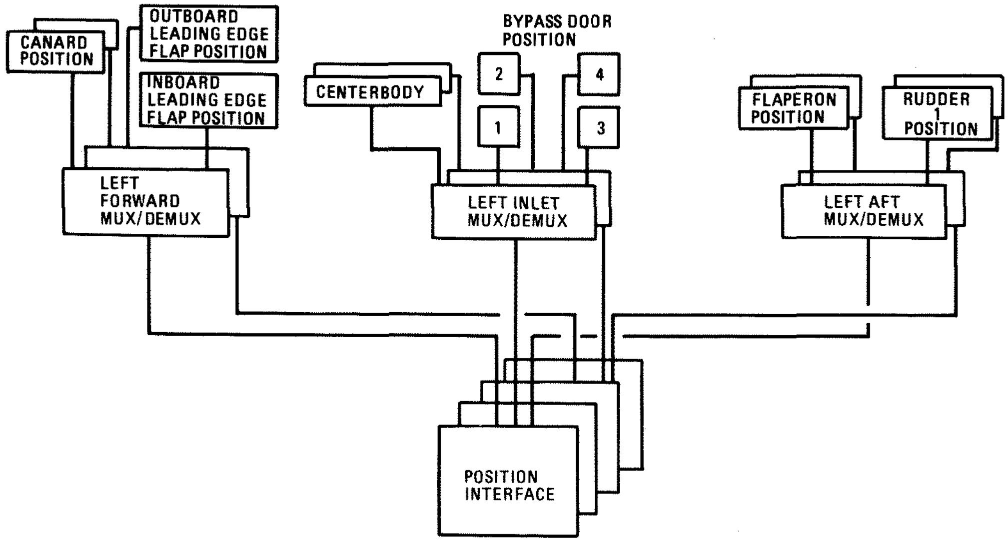

Figure 19. Position Mux - Inlet and Surfaces

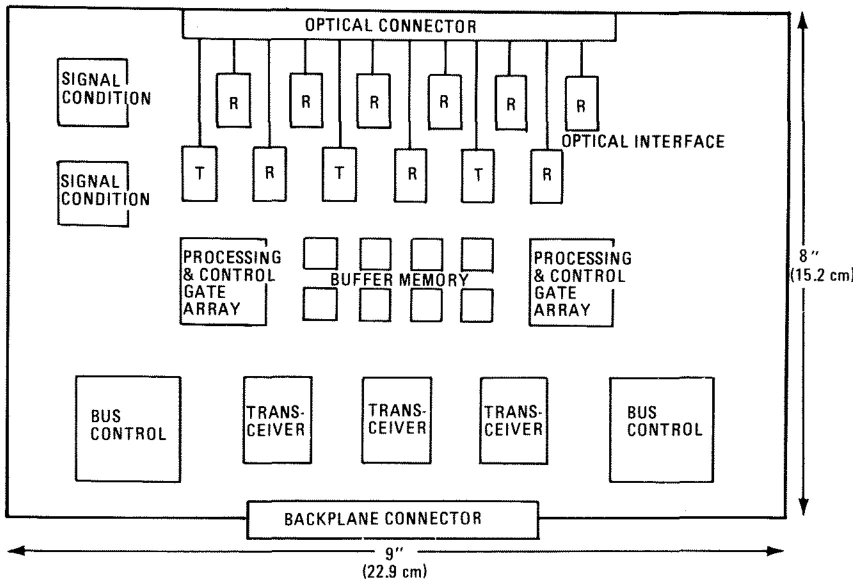

Figure 20. Pressure Sensor Interface Layout

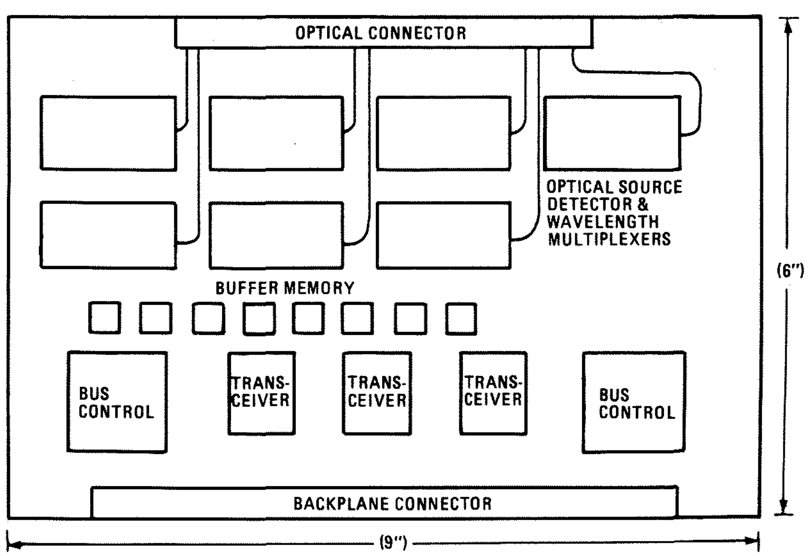

Figure 21. Position Sensor Interface Layout