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NASA Contractor Report 165963

INTEGRATED APPLICATION OF ACTIVE CONTROLS (IAAC) TECHNOLOGY TO AN ADVANCED SUBSONIC TRANSPORT PROJECT–

ACT/CONTROL/GUIDANCE SYSTEM STUDY–VOLUME I

FINAL REPORT

BOEING COMMERCIAL AIRPLANE COMPANY
P.O. BOX 3707, SEATTLE, WASHINGTON 98124

CONTRACT NAS1-15325
December 1982

[redacted]

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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

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X83-10067#

FOREWORD

This document constitutes the final report of the ACT/Control/Guidance System Definition Task of the Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project. The report covers work performed from December 1980 through January 1982 under Contract NAS1-15325.

Volume I contains the principal results of the study, and supplementary technical data are contained in Volume II.

The NASA Technical Monitor for this contract task was D. B. Middleton of the Energy Efficient Transport Project Office at Langley Research Center.

The work was accomplished within the Preliminary Design and Engineering Technology Departments of the Vice President—Engineering organization of Boeing Commercial Airplane Company. Key contractor personnel who contributed were:

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During this study, principal measurements were made in U.S. customary units and were converted to Standard International units for this document.

Use of trade names or names of manufacturers in this report does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

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1.0 SUMMARY

This report documents the ACT/Control/Guidance System portion of the Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project, a part of the NASA Energy Efficient Transport (EET) Program. There were two major subtasks: (1) Functional Analysis and (2) System and Simulation Definition Requirements.

The objectives of the Functional Analysis subtask were to:

- Define the air traffic environment of the 1990s with respect to (1) the probable airborne system complement of a commercial transport operating in that era and (2) the possible effects on operations of an airplane with active controls
- Assess the airplane systems technology level expected by the 1990s
- Identify the Active Controls Technology (ACT) airplane flight functions in a top-down listing, together with the criticality to safety of flight associated with the ACT-related and control/guidance functions

The objectives of the System and Simulation Definition Requirements subtask were to:

- Define an operational function structure for an integrated ACT avionics and flight deck system that would meet the operational requirements and functional objectives of the function analysis
- Define the scope and requirements of a program for simulation of the integrated ACT avionics and flight deck system with pilot in the loop, in terms of simulation scenario, ACT avionics and crew system elements simulated, and the recommended mechanization

It was determined that the ACT airplane considered in this study is compatible with current and anticipated air traffic control procedures.

The state-of-the-art avionics and flight controls device technology available to mechanize the 1990 ACT airplane systems is expected to allow greater standardized modularization of subsystem elements together with decentralization of control software and reduction of software overhead, validation time, and maintenance burden. This expectation is contingent upon availability of data bus types with interface terminal characteristics such as those described for the Digital Autonomous Terminal Access Communication (DATAC) bus.

The preliminary ACT/Control/Guidance System architecture resulted in four autonomous digital data buses carrying all system traffic exclusive of that dedicated to analog flight crucial Essential Pitch-Augmented Stability. The analog control availability of that function was treated separately. Integration of the functions of sensors, actuators, conventional "avionics," and flight deck controls and displays was accomplished by four main interactive processor groups and by one other autonomous processor group dedicated to flight crucial function processing.

The system architecture remains to be analyzed, verified, and discussed with potential users (the airlines). This should include a thorough analysis of system performance and a piloted simulation to evaluate crew use of the selected system.

The simulation requirements are presented, framed within a detailed scenario of crew flight tasks during each phase of flight, and are in accordance with the ACT avionics and flight deck elements and functions requiring mechanization.

2.0 INTRODUCTION

The Integrated Application of Active Controls (IAAC) Technology to an Advanced Subsonic Transport Project has three major objectives: (1) the credible assessment of the benefit to a commercial jet transport airplane of the full application of active controls designed into the airplane from the beginning of the airplane program, (2) identification of the risks associated with the use of Active Controls Technology (ACT), and (3) reduction of these risks to a level commensurate with commercial practice through test and evaluation.

This project, a part of the NASA-Boeing Energy Efficient Transport (EET) Program, has been organized into three major elements as shown at the top of Figure 1. The first major element included establishment of the design criteria appropriate for an ACT airplane, design of an ACT airplane configuration to meet the selected criteria, design of an ACT control system based upon current technology, and selection and evaluation of a Final ACT Configuration. In parallel with these tasks, the Advanced Technology ACT Control System element included exploration of more direct control law synthesis methods, alternative means of implementing the ACT functions using advanced technology, and the integration study of this report (shown shaded in the figure). The final major element of the IAAC Project will address reduction of risk, associated with implementation of ACT on a commercial transport, through test and evaluation activities. Reference 1 contains a more detailed discussion of the IAAC Project Plan.

The ACT/Control/Guidance System task was undertaken to understand the relationship of the ACT systems to the control and navigation and guidance systems, leading to appropriate functional integration of those systems within the advanced technology and operating environment of the 1990s, and thereafter to define requirements for simulation of the integrated systems with pilot in the loop.

The first part of the report discusses expected operational air traffic control environment of the 1990s (sec 4.0), technology expected of that era as it affects ACT airplane system implementation (sec 5.0), and definition of system function types and their criticalities, which influence integration of crew tasks with ACT/Control/Guidance System functions (sec 6.0). Section 7.0 presents a definition and analysis of a top-down structured system

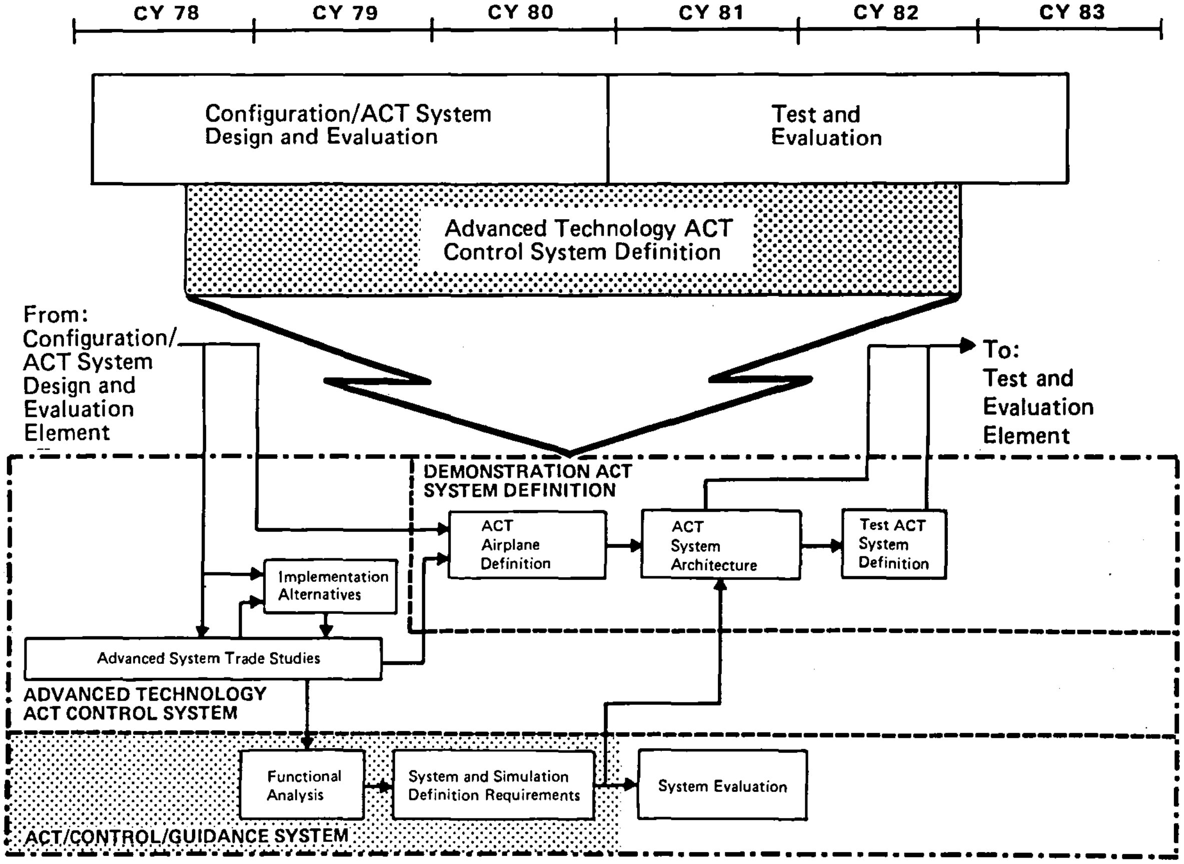

Figure 1. Advanced Technology ACT Control System Definition Element

of integrated active controls, avionics functions, and crew interfaces for a 1990s ACT airplane. Section 8.0 presents the simulation requirements for the necessary pilot-in-the-loop evaluation of the ACT/Control/Guidance System.

This document (vols. I and II) is the complete report on that task work. Volume II contains appendices to the material in Volume I.

3.0 SYMBOLS AND ABBREVIATIONS

This section contains three subsections: General Abbreviations, Subscripts Related to Velocity V or Mach Number M, and Symbols. Each subsection is arranged in alphabetical order.

3.1 GENERAL ABBREVIATIONS

ac	alternating current
alt	altitude
app.	appendix
AAL	angle-of-attack limiting
AAS	aircrew alert system
ACARS	ARINC communication addressing and reporting system
ACP	autoflight control panel
ACT	Active Controls Technology
AD	airspeed display
A/D	analog to digital
ADC	analog-to-digital converter
ADD	attitude director display
ADF	automatic direction finder
ADP	air data processor
ADS	air data sensor
ADSEL	address beacon surveillance system
AERA	automatic en route ATC
AFCS	automatic flight control system
AGL	above ground level
AHRS	attitude heading reference system
AIDS	airborne integrated data system
AIM	acknowledgment, ISO alphabet No. 5, and maintenance
ALCM	air-launched cruise missile
ALPG	autoland processor group
ALU	arithmetic logic unit
AOA	angle of attack
AP	attitude processor

APL	Applied Physics Laboratory
APU	auxiliary power unit
AR	antireflection
ARINC	Aeronautical Radio Incorporated
ARSR	air route surveillance radar
ARTCC	Air Route Traffic Control Center
ARTS	automated radar terminal system
ASCII	American standard code for information interchange
ASDE	airport surface detection equipment
ASR	airport surveillance radar
A/T	autothrottle
ATARS	automatic traffic advisory and resolution service
ATC	air traffic control
ATCRBS	air traffic control radar beacon system (ICAO term: SSR)
ATDP	air-turbine-driven pump
ATIS	automatic terminal information service
bps	bits per second
B	blue
BCAC	Boeing Commercial Airplane Company
BCAS	beacon collision avoidance system
BCD	binary-coded decimal
BITE	built-in test equipment
BMS	body motion sensor
cd	candela
cg	center of gravity
com	communications
C	Celsius
CAD	computer-aided design
CAS	computed airspeed
CAT I, II, III	ILS landing minimums
CCD	charge-coupled device
CCW	counterclockwise
CCZ	coastal confluence zone
CDMA	code-division multiple access
CDTI	cockpit display of traffic information

CDU	control display unit
CML	complementary merged logic
CMOS	complementary metal-oxide semiconductor
CNSP	communication and navigation status panel
CPU	central processing unit
CR	contrast ratio
CRT	cathode-ray tube
CSD	constant speed drive
CSMA	carrier-sense multiple access
CSPD	control surface position display
CW	clockwise
CWS	control wheel steering
CY	calendar year
dB	decibel
dc	direct current
DABS	discrete address beacon system (see Mode-S)
DATAC	Digital Autonomous Terminal Access Communication (System)
DCTTL	diode-coupled transistor-transistor logic
DH	decision height
DIGIVUE	trade name
DITS	Digital Information Transfer System
D/L	data link
DMA	direct memory access
DME	distance measuring equipment
DMOS	dielectrically isolated metal-oxide semiconductor
DOD	Department of Defense
DOT	Department of Transportation
DPG	dedicated pitch gyro
DRO	destructive readout
EAC	expected approach clearance
EADI	electronic attitude director indicator
EAROM	electrically alterable read-only memory
ECL	emitter-coupled logic
ED	engine display
EDP	engine-driven pump

EET	Energy Efficient Transport (Program)
EFL	emitter-follower logic
EGT	exhaust gas temperature
EH	electrohydraulic
EHSI	electronic horizontal situation indicator
E-JFET	enhanced junction field-effect transistor
EL	electroluminescence
EMA	electromechanical actuator
EPR	engine pressure ratio
EPROM	eraseable, programmable read-only memory
ES	engine sensor
ETA	estimated time of arrival
fc	footcandle
fig.	figure
fJ	femtojoule
fL	footlambert
4-D	four-dimensional navigation
F	Fahrenheit
FAA	Federal Aviation Administration
FAD	fuel advisory departure
FAPG	flight augmentation processor group
FAR	Federal Aviation Regulation
FDD	flight deck display
FDM	frequency-division multiplexing
FDMA	frequency-division multiple access
FE	flight engineer
FEA	Federal Energy Administration
FEPG	flight essential processor group
FET	field-effect transistor
FGPG	flight guidance processor group
FID	flight instrument display
FLIR	forward-looking infrared
FMC	flutter-mode control
FMPG	flight management processor group
FS	fuel sensor

g	acceleration due to gravity
G	billion; green
GaAs	gallium arsenide
GHz	gigahertz
GLA	gust-load alleviation
GMT	Greenwich mean time
GPS	global positioning system (formerly NAVSTAR)
GPWS	ground proximity warning system
GS	glide slope
G/S	ground speed
h	altitude
hp	horsepower
HDD	head-down display
HF	high frequency
HHUD	holographic head-up display
HMOS	high-performance metal-oxide semiconductor
HOL	higher order language
HSD	horizontal situation display
HSI	horizontal situation indicator
HUD	head-up display
inHg	conventional inch of mercury
IAAC	Integrated Application of Active Controls Technology to an Advanced Subsonic Transport Project
IAP	integrated actuator package
ICAO	International Civil Aviation Organization
IEEE	Institute of Electrical and Electronic Engineers
IFR	instrument flight rule
I^2L	integrated injection logic
ILS	instrument landing system
IMC	instrument meteorological condition
INS	inertial navigation system
I/O	input/output
IR	infrared
IRS	inertial reference system
ISA	ICAO standard atmosphere

ISL	injection Schottky logic
ISO	International Standards Organization
JFET	junction field-effect transistor
kHz	kilohertz
kn	knot
kPa	kilopascal
kV	kilovolt
kW	kilowatt
K	thousand
KCAS	knots calibrated airspeed
KEAS	knots equivalent airspeed
lb/in^2	pounds per square inch
lm/W	lumen per watt
Loran-C	long-range navigation, type C
lx	lux
L	length
LAS	lateral/directional-augmented stability
LC	liquid crystal
LE	leading edge
LED	light-emitting diode
LOC	localizer
LRU	line replaceable unit
LSI	large-scale integration
LSIC	large-scale integrated circuit
LSTTL	low-power Schottky transistor-transistor logic
mbar	millibar
mil	mil
min	minute
Mode-S	new ICAO-standard selective-address ATCRBS mode (see DABS)
ms	millisecond
mW	milliwatt
μm	micrometer
μs	microsecond
μW	microwatt
M	Mach; million

MAC	mean aerodynamic chord
MB	marker beacon
MESFET	metal semiconductor field-effect transistor
MFD	multifunction display
MFK	multifunction keyboard
MFP	multifunction panel
MHz	megahertz
MIL-STD	military standard
MLC	maneuver-load control
MLS	microwave landing system
MLW	maximum landing weight
MNOS	metal-nitride-oxide semiconductor
MOS	metal-oxide semiconductor
MOSFET	metal-oxide semiconductor field-effect transistor
MPa	megapascal
M&S	metering and spacing
MSAW	minimum safe altitude warning
MSL	mean sea level
MSPP	mechanical servo power package
MTBF	mean time between failures
MTOGW	maximum takeoff gross weight
MZFW	maximum zero fuel weight
nm	nanometer
nmi	nautical mile
npn	negative-positive-negative
ns	nanosecond
N1	low-speed compressor RPM
N2	high-speed compressor RPM
N/A	not available
NAS	National Airspace System
NAV	navigation
NAVSTAR	(see GPS)
ND	navigation display
NDB	nondirectional beacon
NDRO	nondestructive readout

NMOS	negative metal-oxide semiconductor
NV	not volatile
Omega	very-low-frequency navigation system
O	orange
OEW	operating empty weight
pJ	picojoule
pnp	positive-negative-positive
ps	picosecond
PA	public address
PAR	precision approach radar
PAS	pitch-augmented stability
PBT	permeable-base transistor
PDME	precision distance measuring equipment
PFC	pilot flight control
PMOS	positive metal-oxide semiconductor
PROM	programmable read-only memory
PS	pneumatic sensor
PTA	planned time of arrival
q	body pitch rate
rad	radian
ref	reference
r/min	revolutions per minute
rms	root mean square
R	red
RALT	radio altimeter
RAM	random-access memory
RC	resistance times capacitance
RCA	company name
RFI	radiofrequency interference
RMD	radio magnetic display
RMI	radio magnetic indicator
RNAV	area navigation
ROM	read-only memory
RPM	revolutions per minute
RVR	runway visual range

RW	runway
RZ	return to zero
s	second (same as sec)
sec	second (same as s)
SD	system display
SDFL	Schottky diode FET logic
SELCAL	selective calling
Si	silicon
SID	standard instrument departure
SOCMOS	selective-oxidation CMOS
SOISMOS	silicon on insulated substrate MOS
SOS	silicon on sapphire
SPS	surface position sensor
SRAM	short-range attack missile
SSB	single sideband
SSD	system status display
SSR	secondary surveillance radar (U.S. term: ATCRBS)
STAR	standard terminal arrival route
STTL	Schottky transistor-transistor logic
SX	longitudinal distance from runway threshold (positive forward)
SY	lateral offset from runway centerline (positive right)
TACAN	tactical air navigation
TBD	to be determined
TCAS	Traffic Alert and Collision Avoidance System
TCD	time-critical display
TDM	time-division multiplexing
TDMA	time-division multiple access
T_D	propagation delay
TE	trailing edge
TED	transfer electronic device
TFEL	thin-film electroluminescence
TFT	thin-film technology
T-NAV	four-dimensional navigation (see 4-D)
TOD	top of descent
TOLD	takeoff and landing data

TR	transformer-rectifier
TSO	technical standard order
T_T	total air temperature
TTL	transistor-transistor logic
TV	television
u	incremental value of forward velocity
UHF	ultra high frequency
UV	ultraviolet
vol.	volume
V	volt; volatile
VAC	voice-activated control
VASI	visual approach slope indicator
VAX	vertical address extended (computer)
V_C	airspeed
VFR	visual flight rule
VHF	very high frequency
VHSIC	very-high-speed integrated circuit
VLF	very low frequency
VMC	visual meteorological condition
VMOS	V-groove metal-oxide semiconductor
VOR	very-high-frequency omnidirectional range
VORTAC	combined VOR and TACAN
VSD	vertical situation display
V_T	true airspeed
W	watt
WLA	wing-load alleviation
WMS	wing motion sensor
Wshld	windshield
XPOND	transponder
Y	yellow
$\ddot{z}$	body normal acceleration
ZnS	zinc sulfide
ZnS:Cu	copper-activated zinc sulfide
ZnS:Mn	manganese-activated zinc sulfide

3.2 SUBSCRIPTS RELATED TO VELOCITY V OR MACH NUMBER M

D	dive
e	equivalent airspeed
LO	liftoff
MO	maximum operating
REF	reference speed
S	stall
1	"go speed," committed on takeoff
2	1.1 times minimum controllable speed with engine out or 1.2 times stall speed

3.3 SYMBOLS

γ	flightpath angle
Δ	change in quantity
δ	control deflection angle
μ	micro
σ	sigma
ϕ	bank angle
ψ	yaw attitude

4.0 ACT AIRPLANE ATC OPERATIONAL ENVIRONMENT OF THE 1990s

This section describes the expected air traffic control (ATC) environment of the 1990s in which the Active Controls Technology (ACT) airplane will operate and defines the avionics equipment and operational capabilities required on board the airplane to interface with the environment. This description is based on current industry and Federal Aviation Administration (FAA) projections and assumptions.

Further, the effect of ACT air traffic control clearances on airplane flight functions and avionics configuration is defined. This was done by comparing relevant characteristics of the Conventional Baseline and Initial ACT Configuration airplane designs to determine which operating characteristics are ATC sensitive.

4.1 ATC GROUND SYSTEM EFFECTS ON AIRBORNE SYSTEM EQUIPMENT

The description of the 1990s ATC system was developed using information from many sources, which described the present system elements, new elements under development, and elements being researched that appear to offer promise as eventual system elements. Supplemental material came from Department of Transportation (DOT) informal industry-review drafts of that agency's extrapolations of the National Airspace System for the 1985, 1990, and 1995 time periods. Reference 2, the FAAs National Airspace System Plan–Facilities, Equipment and Associated Development, which addresses the FAA plan for upgrading the ATC system during the next two decades, was used to establish currency of the 1990s system implementation forecast.

The FAA considered the following factors in making its ATC projection:

- The current FAA major system development program

- The current FAA advanced system development program and its projected output

- The FAA new engineering and development initiatives effort that represents user views with respect to operational philosophy and technology choices for the future

- The best available assessment of the evolution of aircraft and aircraft systems

- Assessment of the shortcomings of present and anticipated systems

- The views of system developers and operators based on their judgment and experience

- Evaluation of available technology and its impact on new hardware and software enhancements and replacements

- Evaluation of the driving forces that will shape the environment, including traffic growth, traffic mix, energy constraints, and budget constraints

The expected traffic demand is key to projecting the nature of the 1990s ATC system. The FAA assumed a traffic forecast with the following characteristics:

- Air carrier instrument flight rule (IFR) operations growth will average 1.9% per year through the coming decade.

- General aviation IFR growth will average 6% per year, and general aviation aircraft and hours flown will nearly double in the next two decades.

- Air taxi (including commuter) IFR growth will average 7.4% per year.

- Military IFR growth will remain constant.

- Demand on FAA Air Route Traffic Control Centers (ARTCC) will increase at just over 3% per year and therefore will experience a 50% increase in activity by 1991.

- Peak demand levels will become more severe.

- The traffic mix will become more heterogeneous.

- Airport congestion will create ATC backups into the en route airspace.

- The number of helicopters and helicopter operators will continue to grow at a high rate. City-center to city-center operations are expected to be commonplace by the end of the 1990s.

The following subsections describe the 1990s ATC system in three parts: (1) those electronic system elements that play a direct role in controlling aircraft, (2) the automation computer programs that will provide the controller with increased capability beyond what can be done without computer assistance, and (3) the levels of ATC service that may be expected in differently defined airspace resulting from variations in traffic density and types of aircraft operations. Figure 2 summarizes the projected ATC environment for the 1990s.

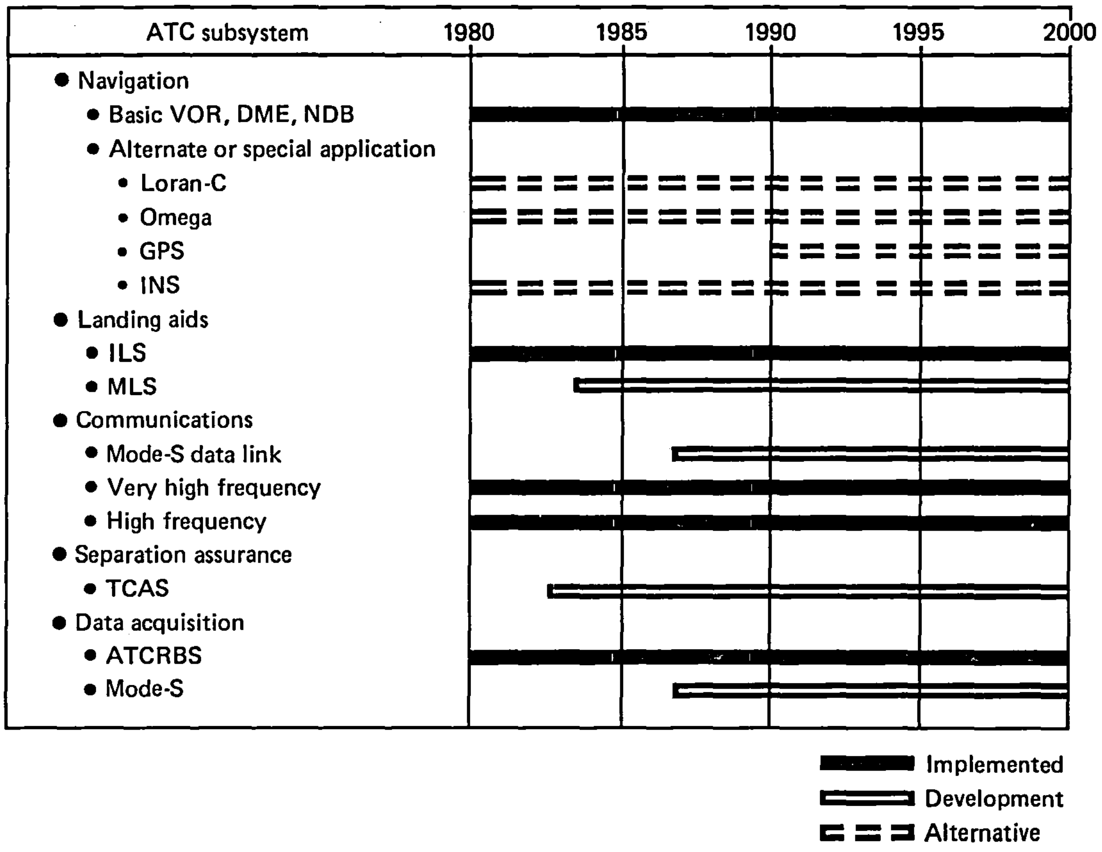

Figure 2. U.S. Air Traffic Control Environment in the 1990s

4.1.1 SYSTEM ELEMENTS

The ATC system provides air traffic services, aeronautical mobile communications, aeronautical navigation services, and landing aids. Data acquisition and separation assurance systems augment and/or back up these air traffic services.

4.1.1.1 Data Acquisition

The present International Civil Aviation Organization (ICAO) standard system for providing data for en route and terminal area ATC is the air traffic control radar beacon system (ATCRBS). It is a secondary radar system (an interrogator-transponder system), in which a transponder carried on the airplane provides flight identity information (and altitude if an altitude encoder is carried) in response to ground-based discrete interrogation. The interrogator also determines airplane position (range and azimuth relative to the interrogator location).

ATCRBS performance degrades in areas of high traffic density, and the FAA is developing a new beacon mode that will overcome much of the ATCRBS problems by selectively interrogating or addressing each flight. This new mode, called Mode-S, is fully compatible with the ATCRBS and is intended initially for use in high-density airspace. Mode-S can also function as a two-way digital data link between ATC and the airplane. Mode-S is expected to have an initial operating capability in 1986-87, and by the 1990s will be the primary data acquisition system for both high-density terminal areas and en route sectors. The United Kingdom has developed a similar selective address beacon surveillance system (ADSEL), which is intended to be completely compatible with Mode-S. It is expected that ICAO will eventually standardize on an ATCRBS-compatible Mode-S system in the international system for ATC data acquisition. The Mode-A and Mode-C ATCRBSs will continue to be used in U.S. low-density airspace for some time because of the cost of replacing all Mode-A and Mode-C interrogators with Mode-S interrogators. Elsewhere, Mode-A and Mode-C ATCRBSs may be used until well into the next century, although the Mode-S system may be used in the more developed areas.

The Mode-S surveillance system requires a special Mode-S transponder on the airplane to allow selective addressing and to provide data link service. An ATCRBS-transponder-equipped airplane will receive service in Mode-S airspace; however, Mode-S transponders will eventually be required because of potential problems. Conversely, Mode-S transponders function as ATCRBS transponders in ATCRBS airspace.

Surveillance coverage (using Mode-S) will be provided at 1830m (6000-ft) mean sea level (MSL) and above and during approaches to qualifying airports. The surveillance system comprises en route and terminal radar and beacon systems. By 1990, Mode-S and data link coverage will be provided above 3810m (12 500-ft) MSL to designated airports. By the year 2000, data link coverage will be extended from 3810m (12 500-ft) MSL down to 1830m (6000-ft) MSL. Primary radar will be retained for FAA weather and ATC requirements until the 1990s. Primary en route radar will be gradually replaced by the next-generation weather radar and finally eliminated by the year 2000.

The concept of cockpit display of traffic information (CDTI) is being examined as a means of allowing the pilot to control his own flightpath in response to limited ATC clearances such as "maintain 8 km (4.3 nmi) in-trail behind flight XXXX." If such a system were to be developed, the airplane would require special communications, data processing, and control and display equipment and could require changing the flight deck to resolve workload problems.

Airport surface detection equipment (ASDE) is a primary radar system that gives the controller a pictorial presentation of the airport surface area and the relative position of the aircraft on that surface. The system aids the efficient and expedient movement of aircraft on the airport surface, thus promoting safety and improved operations rates. Currently, ASDE-2 is the only data acquisition system in use for airport ground surveillance. After 1989, the solid-state ASDE-3 will replace all ASDE-2 installations.

4.1.1.2 Separation Assurance

A system under development, Traffic Alert and Collision Avoidance System (TCAS), is designed to provide independent, backup separation assurance to air traffic control.

TCAS-I and TCAS-II operate independently of the ground. The basic unit, common to both systems, is an integral transponder capable of operating on Mode-A, Mode-C, and Mode-S* (with surveillance, COMM-A, COMM-B, and COMM-C message format capabilities).

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*Mode-A, Mode-C, and Mode-S comprise the basic discrete address beacon system (DABS) ICAO transponder capability. Mode-A alone is the basic civil and military mode for ATC use. Mode-C refers to the addition of altitude information. Mode-S refers to the new selective address capability of DABS. Non-DABS (or non-Mode-S) beacons have either a Mode-A or Mode-A plus Mode-C capability. The term "DABS" has been dropped from the FAA lexicon.

TCAS-I is the simpler of the two systems and is intended primarily for general aviation aircraft. It should be able to receive (from TCAS-II equipped aircraft) and display (1) traffic advisory information (range, relative azimuth that can be converted to a relative bearing, relative bearing that is independent of relative azimuth when available, and differential altitude) and (2) nearest approach prediction of the intruder TCAS-II aircraft. TCAS-I, as yet undefined, would receive and display (1) sensitivity-dependent, non-altitude-filtered range information from Mode-A and Mode-C and from Mode-A transponders within ATCRBS or secondary surveillance radar (SSR) using Mode-A, Mode-C, and Mode-S ground station coverage and (2) altitude-filtered range information from Mode-S squitter transmission generated by other TCAS-I and Mode-A, Mode-C, and Mode-S transponders in all airspace. TCAS-I sensitivity would be controlled manually.

Growth capability includes the ability to (1) altitude-sort sensitivity-dependent information on ATCRBS Mode-A and Mode-C transponder-equipped aircraft within the ATCRBS or Mode-A, Mode-C, and Mode-S ground station coverage and (2) provide simple o'clock position of threat display, based on use of a simple directional antenna.

TCAS-II equipment is intended for air carrier application. It consists of a basic Mode-A, Mode-C, and Mode-S transponder; a collision avoidance interrogator; collision avoidance logic and data processor; and appropriate controls, displays, and antennas. TCAS-II will provide collision avoidance protection independently of the ground ATC system, using vertical avoidance maneuvers (TCAS-I does not provide collision avoidance commands).

The TCAS-II collision avoidance operation is similar to the operation of the active beacon collision avoidance system (BCAS) with the added capability of directional sensing. TCAS-II will function through transponder replies it receives from aircraft and will use these inputs to calculate range, relative altitude, and closing information in relation to the aircraft that are possible collision threats. When a "projected time to collision" is about 30 sec, TCAS-II will indicate recommended avoidance maneuvers (vertical) on the TCAS display on the subject aircraft. The azimuth sensing capability will be used for horizontal miss distance assessment and the generation of horizontal resolution advisories. The directional antenna also provides solutions to the problems of synchronous garble, which can occur when several aircraft are interrogated simultaneously. This is accomplished by limiting or rationing the interrogation energy to those directions where it is most needed.

TCAS-II can transmit traffic advisory information (range, relative azimuth, relative bearing, differential altitude, and information on any maneuver being executed) to other TCAS-I and TCAS-II equipped aircraft.

TCAS-II will have an integral scanning antenna system (or equivalent) with direction-finding accuracy sufficient to present an o'clock display (±8 deg, 1σ) centered on the TCAS-II aircraft. It will also have sufficient accuracy to transmit north-reference relative azimuth advisory information to TCAS-I and TCAS-II equipped aircraft with an accuracy of ±9 deg, 1σ.

The TCAS-II aircraft display will be altitude filtered for Mode-C equipped targets and will warn of threatening aircraft within designated display ranges on a display of the user's choice.

A TCAS-II sensitivity adjustment, independent of the ground ATC system, will be provided.

4.1.1.3 Communications

The very-high-frequency (VHF) voice system will remain the basis for continental United States ATC ground-air communications. Voice communication coverage to towers, ATC centers, and flight control stations will be provided at or higher than 600m (2000 ft) above ground level. Existing and future radiofrequency requirements will make conversion of ground and airborne systems to 25-kHz spacing necessary. Military aircraft will use ultra high frequency (UHF). Beginning with selected routine messages, the Mode-S data link, where available, will gradually assume the load for most normal ATC air-ground communications. Initially, the Mode-S data link is being considered for takeoff-clearance and altitude assignment confirmations, minimum safe altitude warning (MSAW) advisories, and various weather data. Planned future messages include enhanced en route weather, downlink weather data, ATC instructions, metering and spacing (M&S) instructions, hazardous precipitation, flight plan filing, clearance delivery, and Category I and II protection status. The Mode-S data link is a candidate means of uplinking data for the CDTI, and eventually all ATC clearances may be provided by the Mode-S data link.

Avionics required for Mode-S data link operation, in addition to the Mode-S transponder, will include data link interface electronics, message input device, and message display equipment.

The Mode-S data link will be mandatory only in designated airspace. VHF voice will continue to provide service to the user without data link, for nonroutine communications to data link users, and in airspace not covered by Mode-S surveillance.

Over most oceanic areas and certain ground areas not equipped with the VHF system, long-range ground-air ATC communications will be accomplished by the high-frequency (HF) communication system. This system may be supplemented by a satellite communication system when that technology becomes more cost effective.

4.1.1.4 Navigation Aids

The very-high-frequency omnidirectional range (VOR) is the ICAO standard short-range navigation aid. VOR provides a magnetic bearing from the airplane to the VOR ground station. It is protected by international agreement to 1985, and the protection is expected to be extended. The FAA is upgrading U.S. VOR facilities, indicating expected use as the standard U.S. navigation aid into the 1990s. The nation's count of 884 VOR (VOR-DME and/or VORTAC) facilities will grow to 960 facilities by 1999.

Distance measuring equipment (DME) measures distance from a DME ground station and is the ICAO standard short-range navigation aid that provides for more precise navigation than VOR alone. These two aids (VOR and DME) are generally colocated for most efficient use. ICAO plans no changes in its DME standards before 1985. DME is the distance part of the U.S. Department of Defense (DOD) standard short-range tactical air navigation (TACAN) system. Thus, VOR and DME will be the standard navigation aids for the United States in the 1990s.

In addition to VOR and DME, some nondirectional beacons (NDB) will be used; NDB systems are nondirectional radio transmitting stations. Aircraft equipped with automatic direction finders (ADF) receive signals to obtain a bearing relative to vehicle heading. Beacons transmit in radiofrequency bands of between 200 to 415 kHz over ranges from 18 to 650 km (10 to 350 nmi), depending on location, operational objective, and power. Bearing accuracy is about ±3 deg.

NDBs are used during the transition from en route to airport precision approach facilities and as a nonprecision approach aid at many smaller airports. NDBs also provide radio aid for flight navigation where VOR coverage is not available. In Alaska they are an integral part of low-altitude airway structure. The beacons may also relay transcribed weather broadcasts.

The FAA operates 215 NDBs. In addition, there are about 500 nonfederally operated aeronautical beacons. During the next 10 years, FAA beacon expenditures are planned to be limited to the occasional relocation or establishment of an NDB for instrument landing system (ILS) transition, replacement of deteriorated components, and modernization of selected facilities, thereby increasing the number of FAA-operated NDBs to 263 by 1999.

Several other navigation aids may be used for special applications. These aids include the Omega very-low-frequency system, the satellite-based global positioning system (NAVSTAR), and Loran-C. The global positioning system (GPS) is being considered as a possible successor to VOR and DME. In addition, an inertial navigation system (INS), probably in combination with a navigation aid, will be certified for area navigation.

Omega–Omega is a VLF long-range navigation system being implemented by the U.S. Navy. In addition to DOD air and marine users, commercial and private ships are using the Omega system. Certain intercontinental air carriers are using Omega to bound the errors of their self-contained navigation systems and also as a standalone navigation system.

GPS (NAVSTAR)–GPS is being developed by the DOD and is intended to provide positioning primarily for weapon delivering systems, as well as a number of other military missions. It will use satellites to provide worldwide, continuous, real-time, all-weather precision information to users operating equipment in a passive mode.

The FAA and NASA are investigating GPS for potential application in the civil sector. If implemented, the degree of its acceptance for civil use will be especially sensitive to the successful design of low-cost user equipment. The use of GPS by the international civil community raises institutional questions on system management that need further examination. While present design predictions indicate that GPS for civil use is not expected to be accurate enough to replace precision landing systems, it may have a technical potential for nonprecision approaches to any airport in the world.

Loran-C—The Loran-C is a pulsed, hyperbolic navigation system operating on 100 kHz. Groundwave range is typically 1100 to 2600 km (600 to 1400 nmi) over seawater. Predictable accuracy of position information is at least 0.46 km (0.25 nmi) (2σ root mean square) in advertised groundwave coverage areas when using automatic receivers of current design. The repeatable accuracy of the system is 18m to 90m (60 to 300 ft). With the exception of one station operated by the Government of Canada, the stations providing coverage for the United States are operated by the U. S. Coast Guard.

In 1974, Loran-C was designated as the U.S. Government-provided navigation system for the coastal confluence zone (CCZ). The implementation plan provides complete Loran-C operational coverage for the CCZ of the contiguous 48 states and southern Alaska.

Because Loran-C stations must be land based and have a useful range of about 1850 km (1000 nmi), it is not feasible to provide a worldwide system using this technique. This coverage is fixed by the area where an adequate signal-to-noise ratio is available, as the system is noise limited.

Loran-C navigation is not currently being installed by scheduled air carriers, and future use is unlikely because it cannot provide worldwide coverage for long-range navigation and is unlikely to be selected by ICAO for short-range navigation.

4.1.1.5 Landing Aids

Precision instrument approaches are presently based on the ILS. The ILS is protected by international agreement through the ICAO as the standard precision approach aid through 1995. A new precision approach aid called the microwave landing system (MLS) has been approved by the ICAO and is expected to be colocated initially with ILS and to replace it eventually.

Instrument Landing System—ILS ground equipment consists of a localizer facility, a glide slope facility, and two or three marker beacons. The localizer provides horizontal guidance about the runway centerline with extended coverage from at least 33 km (18 nmi) to touchdown. The localizer signal emitted from the far end of the runway is adjusted to produce an angular width between 3 and 6 deg as necessary to provide a linear width of approximately 210m (700 ft) at the runway approach threshold. The localizer transmits in the 108- to 112-MHz band. The glide slope facility provides vertical guidance to an approaching aircraft. The glidepath angle is normally 3 deg above the horizontal. Marker beacons indicate to an approaching aircraft the distance to runway threshold. The glide slope device transmits in the 328- to 335-MHz band, and the beacons transmit at 75 MHz. Most ILSs provide Category I landings with a decision height (DH) of 60m (200 ft) and a runway visual range (RVR) of 550m (1800 ft). Some systems have improved capabilities providing Category II, DH 30m (100 ft), RVR 400m (1200 ft); Category IIIA, DH 0, RVR 200m (700 ft); and Category IIIB, DH 0, RVR 50m (150 ft) landings.

The FAA presently operates 752 full ILS facilities, each providing aircraft with vertical and horizontal guidance with respect to a particular airport runway. Additional facilities are operated by agencies other than the FAA. About 50 additional systems will be required by the ILS purchase cutoff date of 1983 to meet specific traffic requirements or to provide service at new airports. In addition, ILS facilities are operated by the DOD in the United States.

ILS avionics equipment is required by Federal air regulation to be carried by most U.S. air carrier aircraft. It is used extensively by general aviation aircraft and is required for some IFR approach and landing operations. The equipment is also used extensively by aircraft of other countries, both air carrier and general aviation, because it is the ICAO landing aid standard.

Terrain considerations are a factor in the installation of ILS (e.g., signal reflections (multipath) from the ground, taxiing aircraft, and other surface traffic). The single-approach path provided by an ILS constrains airport capacity and noise control. In regions where many airport runways require ILS, the saturation of current 100-kHz separated radiofrequency channels could be the limiting factor for the number of installations.

Microwave Landing System—The MLS is a joint development of the DOT, DOD, and NASA under FAA management. Its purpose is to provide a civil and military, Federal and non-Federal standardized approach and landing system with improved performance and flexible implementation as compared with existing landing systems.

Approach and landing navigation information is aircraft derived, based on ground-transmitted signals. Elevation and azimuth angle signals, combined with a precision distance measuring equipment (PDME) capacity, provide data over a wide volume (e.g., ±40 deg in azimuth from runway centerline and 2 to 20 deg in elevation). The signal format lends itself to a variety of implementation forms ranging from simple and inexpensive to complex. The more complex systems enable landing under zero visibility conditions.

After a period of coexistence, MLS is expected to replace the existing ILS. Currently, the ILS is protected by the ICAO through 1995. The FAA expects to start installing MLS facilities in 1983, with 15 systems in place by 1987. The installation rate will peak at 110 per year in 1985 and will continue at that rate until all 1255 systems are in place.

An airborne MLS consists of the MLS receiver and an antenna system that provides signal reception for all aspect angles expected to be used in the MLS.

4.1.1.6 Aircraft Equipment

Table 1 lists current equipment for air carrier navigation from point to point. Most of these items are cited as ICAO requirements for long-distance civil air navigation. These requirements normally reflect the demands of current operational environments. Table 1 also lists applicable regulations.

Table 1. Aircraft Navigation Equipment Currently Used in the Air Traffic Control Environment

Navigation equipment	Federal Aviation Regulation (FAR)	Technical standard order (TSO)	Advisory Circular	Number required
VOR	121.349a, e	C40a	90-45A	2
DME	121.349c	C66a	90-45A	1
LOC/GS	121.349a	C34b	120-28A	1
		C36b	120-29	–
MB	121.349a	C35c	–	1
ADF	121.349b	C41b	20-63	1
INS/ISS	121.355	–	25-4	2
	121, App. G	–	121-13	–
RNAV	–	–	90-45A	–
Omega	–	–	120-31	–

Table 2 summarizes a typical airline navigation system and equipment list as published by the European Airlines Electronic Committee. (Although not shown here, altitude and heading systems are also an integral part of the navigation equipment complement.)

Table 2. Typical Airline Navigation System and Equipment List

Equipment	Quantity	ARINC documents
VHF communications	3	716
DME	2	709-1
VOR	2	711-1
LOC/GS	2	710-2
Radio altimeter	2	707-1
Marker	1	711-1
Weather radar	2	708-1
ADF	2	712-1
INS/AHRS	3	704, 705

Table 3 lists the equipment needed to interface electrically with the 1990s ATC system in all levels of airspace.

Table 3. Avionics for Air Transport Operations in 1990s Air Traffic Control Environment

System	Application	Avionics
• Data acquisition		
• ATCRBS with Mode-S	• Mode-S-equipped transponder required on air carrier aircraft	• Mode-S transponder
• Separation assurance		
• TCAS	• Required for all air carriers	• Interrogator, controls, and displays
• Communications		
• VHF voice	• Most U.S. domestic and foreign ATC operations	• VHF transceiver
• Mode-S D/L	• High-density U.S. airspace	• Mode-S data link modem and I/O devices
• HF SSB	• Overocean and lesser developed overland air routes	• HF SSB transceiver
• Navigation aids		
• VOR	• Required for short-range navigation	• Receiver
• DME	• Required for short-range navigation	• Interrogator
• NDB	• Needed for navigation and approach guidance in some areas	• Automatic direction finder
• INS	• Used for long-range navigation independently or with other systems (e.g., for position fixing)	One or more types needed for long-range navigation; INS installation must be at least a dual system
• Omega	• Used for long-range navigation independently or to position-fix INS in either VLF or Omega modes	
• GPS	• May find use for either short- or long-range navigation or to position-fix INS	
• Landing aids		
• ILS	• Required until 1995 or until all destination runways have MLS	• ILS localizer, glide slope, and marker beacon receivers
• MLS	• Required after 1995 but needed before to obtain improved landing guidance available at runways where implemented	• MLS receiver

4.1.2 CONTROL SYSTEM

The control system is that portion of the ATC system that assesses the traffic situation and determines the actual route, altitude, and speed each flight is expected to use at any time to resolve the traffic situation. The objectives of this control process are safe separation of the flight from other aircraft, severe weather, and terrain; direct routing of the flight to its destination; and metering, sequencing, and spacing flights for landing.

The present control system is essentially manual in that the situation assessment and decisions are accomplished by the controller. Automation programs are being developed to assist the controller in the control of traffic. Control at the highest level is evolving from today's manual radar-assisted system of control, based on the relative spacing between aircraft, toward an automated time-based system in which separation and spacing are inherent in the four-dimensional (4-D) flight schedule assigned to each aircraft.

The control system of the 1990s will minimize global fuel usage by reducing airborne delay and using fuel-efficient flight profiles. Clearances based on two-, three-, and four-dimensional area navigation will be used extensively. To accomplish this, the system will use advanced ATC computer programs and airborne flight management system capabilities.

The following paragraphs describe FAA programs that are presently in the research and development phase and concentrates on those programs expected to become part of the 1990s integrated control system.

A national integrated flow management system will match the en route traffic flow pattern to existing air route and airport capacity on a nationwide basis. By using data on the destination airport capacity expected at the time of arrival and the total traffic demand forecast at that time, the national integrated flow management system will allow all but a few minutes of the expected delay to be taken on the ground at the departure airport. This management system will be an improvement over the existing central flow control facility. Automation programs that are presently used and may become part of the national integrated flow management system include:

- Fuel Advisory Departure (FAD) Procedures—These procedures are currently applied at Chicago and Denver. As implemented, the aircraft operator is offered the option of delaying his departure until ATC can absorb the flight with no more than about a 30-min arrival holding delay at destination. This concept reduces engine running time and fuel consumption while at the same time reduces the occupancy of the airspace in terminal areas during times of congestion or delay-causing weather phenomena.

- Expanded Metering Program—Expanded metering is another FAA metering program (in effect at Denver). In expanded metering, when expected Denver delays are 30 min or more and a nonstop flight originating within 75 min (flight time) of Denver is ready to depart, the flight is placed in the Denver metering list and a time to enter the Denver terminal area is calculated. The flight may take all but 10 min of the expected delay on the ground. It will then have only a 10-min airborne arrival holding delay.

An integrated terminal area flow management system will be the basic means for controlling aircraft to achieve optimum airport throughput and optimum fuel performance of participating aircraft. En route and terminal area control will be integrated, and arrival metering will start during the en route portion of the flight. Wake vortex avoidance systems, airport configuration management aids, and airplane flight management system capabilities will be considered in developing the control clearances for metering flights into the terminal area. This impacts sequencing and spacing for landing.

Automation programs that are being developed and can be expected to become part of the integrated terminal area flow management system include:

- Metering and Spacing (M&S)—This system is designed to automate control in the terminal area. The first phase, basic M&S, is being developed to sequence and space arriving aircraft for landing. It will control arrival traffic using voice vectors and speed commands from the computer-generated controller. A subsequent development, advanced M&S, is expected to expand control to departures, missed approaches, etc., and provide control instructions directly to the pilot via a data link.

- Automatic En Route ATC (AERA)—An AERA-like program will be a primary element of the 1990s automatic ATC systems. AERA will automatically plan conflict-free, fuel-efficient flight trajectories for aircraft operating in positive control airspace. It will generate the ATC clearances needed to execute the planned profiles and ensure aircraft separation and to deliver these clearances via a Mode-S data link. AERA will self-protect against system failure by providing a coast capability and backup clearances and will be compatible with the independent backup separation assurance capabilities of TCAS. Aircraft carrying the Mode-S data link, area navigation equipment, and a flight management computer should be able to take full advantage of the AERA system.

- En Route Metering—En route metering will control all en route traffic coming toward an airport to enable matching the flow rate into the terminal area to the runway acceptance rate. Functionally, it is automation of a procedure similar to the present Denver local flow management system. Each arrival is controlled from en route cruise through descent into the initial approach fix (called a metering fix) along a path that is both efficient from an aircraft flight standpoint and resolves air traffic conflicts.

  Based on an assigned landing time, a time is determined for each arrival to pass a metering fix and enter the terminal area so that it can nominally fly directly to the runway without delay. Control to meet the metering fix time is initiated during en route cruise using speed control and point-of-descent commands to absorb any delay with a minimum of holding. Eventually, the assignment of 4-D navigation (T-NAV) clearances to 4-D equipped arrivals en route to cruise altitude will allow these flights to meet the assigned metering fix time in the most fuel-efficient manner. Because the AERA program calculates long-term, conflict-free clearances for en route aircraft, an AERA-like program may be combined with en route metering to determine conflict-free 4-D arrival profiles.

Automation programs that will assist the controller in providing safe separation include:

- Minimum Safe Altitude Warning (MSAW)—MSAW is currently implemented as an automated radar terminal system (ARTS-III) terminal area function that automatically alerts the controller when a tracked Mode-C equipped aircraft is below or is predicted by the ARTS-III computer to go below a predetermined minimum safe altitude. A similar en route function is being developed.

- Conflict Alert and Resolution—Conflict alert projects the present flightpath of all aircraft ahead 2 min. System logic determines if separation between any pair will be lost and, if appropriate, alerts the controller to the pending situation. It is presently operational for en route airspace and is being implemented in ARTS-III terminal areas. Conflict resolution is being developed to provide solutions to the controller.

These developments imply an airplane-ATC (pilot-controller) interface that relies upon a catalog of flexible, energy-efficient flight profiles compatible with saturated airspace containing various airplane types. This catalog is resident in both the airplane and ground computers and contains optimum standardization and flexibility to meet variable situations.

4.1.3 LEVELS OF SERVICE

The FAA is projecting several levels of ATC service for the forecast time period that range from highly automated control to no control service at all. Table 4 lists the ATC service levels for the 1990s.

The first level of ATC service will relate to that airspace where all users are full participants and the highest level of ATC automation is required. This high-reliability automatic control system will provide reversion capability to a safe backup automatic control. The automated system will use the Mode-S data link system, which will provide information directly to the cockpit. A level of traffic awareness may be achieved by traffic cockpit displays that are fed from the Mode-S data link or the independent TCAS. Area navigation and the AERA system will be able to accommodate a large number of variables, which will allow a high degree of lateral and vertical routing freedom. Traffic information that may be made available in the cockpit includes moment-to-moment location and projects flightpaths of other aircraft. This can serve to increase the level of traffic awareness. New procedures will be required to ensure that pilot and controller actions are fully understood and coordinated.

Table 4. Levels of Service for Transport Aircraft in U.S. Airspace in 1990s

Level of service	Data acquisition	Separation backup	Communications	Navigation aids	Precision landing aids	Control system
Level 1 • Positive control airspace	• Mode-S	• TCAS	• Mode-S D/L • VHF voice	• VOR/DME	• ILS • MLS	• MSAW • En route metering • M&S • AERA • Conflict alert and resolution • Integrated flow management systems
Level 2 • Mixed IFR-VFR airspace	• Mode-S	• TCAS	• Mode-S D/L and/or VHF voice	• VOR/DME		• MSAW • Conflict alert and resolution • Integrated flow management systems
Level 3 • Procedural airspace	• None except incidental Mode-S coverage	• TCAS	• VHF voice	• VOR/DME • Some NDB		• Manual insertion in flow management systems
Level 4 • Uncontrolled airspace	• None	• TCAS	• None except incidental VHF voice	• None except incidental VOR/DME	• ILS MLS	• None

The first level (and the following lesser levels of ATC service) are still primarily ground-based services based on knowledge of current aircraft position and intent. Ground control and flow management will remain important in en route airspace to ensure fuel-efficient flightpaths and to handle weather reroutes. Terminal and transition airspace analysis to optimize airport and fuel efficiencies is an important requirement. Of course, protection against collisions is a critical issue.

The second level of service will be provided to low- and medium-density airspace to Mode-S equipped aircraft where mixed IFR and visual flight rule (VFR) operations occur. This service will provide efficient operations for ground-based separation assurance services and the airborne TCAS service. Routing freedom may be more limited than in the fully automated first-level environment. Cockpit-displayed traffic information may provide the capability for some self-separation on the part of the pilots; however, direct ground control services will be required in terminal areas.

The third level of service will resemble today's nonradar procedures. IFR operation will be under procedural rules. Depending upon the collision risk level to public transportation aircraft operating on IFR flight plans, aircraft will carry altitude-reporting Mode-S transponders so that TCAS or ATC centers can provide separation assurance. Self-separation may be common in this airspace for the instrument meteorological condition (IMC) to the extent that it can be achieved by using onboard or ground-based surveillance, a Mode-S data link, and a display of close-proximity traffic.

In the fourth level of service, where no ground-based separation service is provided, airborne TCAS equipment may offer some protection in addition to "see and be seen."

4.2 ATC PROCEDURE EFFECTS ON, OR ACCOMMODATIONS FOR, THE ACT AIRPLANE

This study objective defines the operational environment by compiling and categorizing ATC clearances applicable to the ACT airplane time scale so that ACT-sensitive clearances can be identified and the effects on flight functions and avionic configurations defined.

4.2.1 STUDY PROCEDURE

The relevant characteristics of the Conventional Baseline and Initial ACT Configuration designs are compared to determine which operating characteristics are ACT sensitive. Comparisons are based on Reference 3 for the Conventional Baseline and on References 4 through 7 for the Initial ACT Configuration design.

An unpublished Boeing report that tabulates ATC clearances for present and future operational environments, which includes functional capabilities and postulated avionic system tasks dictated by clearances, was used as the ATC clearance data base for this study. That report was reviewed with the goal of identifying those clearances affected by the ACT-sensitive airplane operating characteristics previously defined.

Flight functions and avionic functional capabilities are defined that will permit compliance with these ACT-sensitive ATC clearances.

4.2.2 ACT-SENSITIVE OPERATING CHARACTERISTICS

In most respects, the Conventional Baseline and Initial ACT Configuration designs are similar. The design maximum takeoff gross weight (MTOGW) is the same for both designs. However, the operating empty weight (OEW), maximum zero fuel weight (MZFW), and maximum landing weight (MLW) are all 910 kg (2000 lb) less for the Initial ACT design.

Nominal climb, cruise, and descent speeds are identical for both designs; consequently, the two configurations have similar noise characteristics.

The Initial ACT Configuration does result in reduced empennage drag due to its smaller size, less trim drag due to a farther aft center of gravity (cg), and reduced OEW due to the smaller empennage with its low design air loads. These design improvements result in the following ACT-sensitive operating characteristics:

- Takeoff field length decreased by 4%, 90m (300 ft).
- Landing approach speed decreased by 2%, 1.4 m/s (2.7 kn).
- Tail clearance angle at touchdown reduced from 4 to 3 deg.
- Performance improvements of:
  - A 3.3% decrease, 180 kg (400 lb), in block fuel at average stage length of 863 km (466 nmi).
  - 6% fuel saved at baseline range limit of 3590 km (1938 nmi).
  - A 13% increase in still air range, 472 km (255 nmi), at the fixed-design MTOGW.

An ACT-sensitive cruise characteristic is noted in Reference 4. The Initial ACT Airplane's ability to begin step climb from 10 670m to 11 890m (35 000 to 39 000 ft) at a higher gross weight than the Conventional Baseline Airplane results in a cruise range extension of 204 km (110 nmi). The improved lift-to-drag ratio at cruise allows the Initial ACT Airplane to fly two-thirds of its cruise distance at 11 890m (39 000 ft), compared to the Conventional Baseline Airplane, which must fly two-thirds of its cruise distance at 10 670m (35 000 ft) before being able to step climb to the higher altitude. The difference in step-climb location for the two configurations is about 930 to 1110 km (500 to 600 nmi).

Because of the reduced OEW, 907 kg (2000 lb) of additional fuel load can be carried at the fixed design payloads and MTOGW. If a malfunction occurs that prompts a return to the departure airport, that additional fuel must be dumped to achieve the MLW.

As a fix for an inboard wing flutter problem in the Initial ACT Configuration (refs 4 and 5), a constraint was placed on the transfer of fuel from the structural reserve fuel tanks. Because of the flutter stability added by 1405 kg (3100 lb) of fuel in the wing tips, normal operational and margin speeds are available only with these tanks full. Transfer of fuel from these tanks will normally occur after airplane fuel weight is less than 3175 kg (7000 lb). A reduction in operational and limit speeds will then be necessary to retain appropriate speed margins. Maximum operating airspeed will be reduced by approximately 26 to 36 m/s (50 to 70 kn) due to this procedure. The impact of this limit speed reduction will be minimized due to maximum operating Mach number becoming the limiting high-speed constraint above about 6000m (20 000 ft) and the ATC-imposed speed limit of 129 m/s (250 kn) below 3050m (10 000 ft). Impact is also minimized because transfer of fuel from the structural reserve tanks usually occurs during reserve fuel usage and will not happen during a normal flight.

The Final ACT Configuration design (defined in refs 8 and 9) will have no speed constraints arising from reserve fuel usage because the higher-aspect-ratio wing did not exhibit the same flutter mode and did not result in a structural reserve fuel tank problem.

The Initial ACT Airplane operating envelope boundaries are more sensitive to flight control system faults than the Conventional Baseline design. Depending on which active control modes have failed, and the extent of the failure, four possible flight modifications are required:

- Restrictions on the operating envelope are necessary to provide adequate speed margins when speed pitch-augmented stability (PAS), lateral/directional-augmented stability (LAS), or flutter-mode control (FMC) functions are lost.

- If short-period PAS function redundancy is reduced to only two success paths, or if speed PAS, LAS, and wing-load alleviation (WLA) all fail, safety factors require an immediate diversion to a landing on the nearest adequate runway.
- If angle-of-attack limiting (AAL) or WLA functions fail, special caution must be exercised but no specific restrictions apply.
- When one failure away from loss of PAS (speed), the airplane must be dispatched into a restricted flight envelope.

4.2.3 ACT-SENSITIVE ATC CLEARANCES

A list of present and future ATC clearances (refs 6 and 7) was reviewed to determine which ACT-sensitive operating characteristics could be impacted by clearances. A comprehensive range of clearances was analyzed, including taxi, takeoff, vectoring, route, altitude, speed, holding, approach, and landing clearances, to cover all phases of flight.

Because of the relatively small improvements in takeoff field length and approach speed, no effect on ATC clearances is expected, nor will the reduced tail clearance angle have an impact.

A possible impact on ATC clearances could result from the 10% fuel load increase discussed previously. Burning or dumping that additional fuel in the event of a forced return for landing could require additional coordination with ATC. No specific clearance item can be identified due to this factor; however, holding or vectoring assignments could possibly be affected. The impact would probably be minimal due to the relatively small fuel increase involved and because fuel dumping is an improbable event based on past experience.

Another possible impact on ATC clearances could result from the structural reserve fuel tank effect previously discussed. A 4-D ATC system will use aircraft operating envelope data to generate conflict-free speed assignments. Clearances such as "adjust speed to cross (location) at (time)..." or "increase speed to (amount) knots..." must consider the high- and low-speed boundaries of that particular aircraft. If the high-speed limit is reduced during flight by 26 to 36 m/s (50 to 70 kn), the ATC data base must be updated to ensure that continued aircraft-compatible clearances are generated.

The sensitivity of the operating envelope to flight control system faults could similarly impact ATC clearances. If the high- or low-speed limits for the Initial ACT Airplane change, such as when speed PAS, LAS, or FMC are inoperative, the ATC data base must be updated for continued compatibility.

The required diversion to the nearest adequate runway impacts many types of ATC clearances. Altitude clearances such as "cleared for pilot's option descent to (altitude)" will probably be affected, as will route clearances.

The special caution required by AAL or WLA failures will probably have the greatest impact on speed and altitude clearances. ATC should be aware that clearances requiring prompt compliance are not desirable, as the crew must evaluate the safety factors involved.

The improvement of fuel versus still air range is not expected, in itself, to impact ATC clearances. However, the ability of an ACT airplane to obtain such improvements in fuel efficiency depends on receiving clearance from ATC for the step climb at the desired time. As previously discussed, almost one-half of the cruise range increase possible with the Initial ACT Configuration is due to beginning the step climb 930 to 1110 km (500 to 600 nmi) earlier in cruise. An altitude clearance and possibly a route clearance will be required for this maneuver but may not always be available depending on the traffic situation.

4.2.4 AVIONIC FUNCTIONAL CAPABILITIES DEFINED BY ACT-SENSITIVE CLEARANCES

Table 5 lists ACT-sensitive operating characteristics, associated ATC clearances, impact on ATC, and suggested avionic functional capability. Use of the Mode-S data link is suggested to provide the ATC system with updates on airplane operational speed limits and other constraints.

4.2.5 CONCLUSIONS

ACT-sensitive operating characteristics have been determined and relevant ATC clearances identified. In many cases, either the nature of the operating characteristics precludes any impact on ATC clearances or the change is so small that additional avionic functional capability does not seem warranted.

One item that does suggest additional functional capability is the reserve fuel tank effect on the high-speed limit. Because the Final ACT Configuration design will not reduce the high-speed limit, otherwise incurred by the reserve fuel tanks, no additional functional capability is proposed.

The benefits of the Initial ACT Configuration are substantially dependent on being able to cruise at a higher altitude for a longer distance than the Conventional Baseline. While no additional functional capability is recommended, receiving a clearance for an efficient step climb, or for any other fuel-efficient maneuver, will be most probable when ATC has a data base containing all pertinent airplane performance characteristics.

Table 5. Interaction of the Initial ACT Configuration Design With the Air Traffic Control System

ACT-sensitive operating characteristics	ATC clearances affected	Impact on ATC	Suggested avionic functional capability
Step-climb benefits	Altitude and route clearances	ATC system requires knowledge of optimum step-climb position far enough in advance to attempt rerouting if necessary	None
Reserve fuel effect on high-speed limit	Speed and time assignments	ATC data base must be updated	Restrictions to operating envelope relayed to ATC via Mode-S
910 kg (2000 lb) of additional fuel dumped before landing at MLW	Holding and vectoring	Increased workload when this improbable event occurs	None
Diversion to nearest adequate runway	Altitude, speed, route, approach, and landing	Increased workload with possible manual control techniques when this improbable event occurs	Diversion request and any operating restrictions relayed to ATC via Mode-S D/L
Special caution required due to AAL or WLA inoperative	Clearances requiring prompt compliance	Increased workload with possible manual control techniques for ATC and crew coordination	Request for priority handling relayed to ATC via Mode-S D/L
Restricted operating envelope due to speed PAS, LAS, or FMC failures	Speed and time altitude assignments	ATC data base updated to include current operating envelope	Restrictions to operating envelope relayed to ATC via Mode-S D/L

In summary, no additional avionic functional capability seems to be dictated by consideration of ATC clearances for normal flight operations of the ACT design. Some flight control system failure mode characteristics appear to indicate that if these data (operating envelope restrictions, diversion requests, and priority landing) are relayed to ATC via Mode-S data link, flight safety and efficiency will be enhanced.

5.0 1990s AVIONICS TECHNOLOGY ASSESSMENT

It is difficult to accurately predict the future state of technology. This is particularly true for the avionic technical areas that are discussed in this document. For example, digital electronics has advanced much faster than earlier forecasters predicted. Other technologies, such as flat panel displays, have not developed as fast as many expected. The pace of microelectronics growth continues to confound many experts, especially those who firmly believe that technology responds primarily to demand. Recent advances in microelectronics actually appear to lead the demand for them; i.e., technology applications are developed after the technology advances. Of course, one reason microelectronics has made such rapid advances is that it is not (yet) a capital-intensive industry; hundreds of fiercely competitive small companies entered a field where technical advances depend more on long hours and dedication than on major capital investment.

On the other hand, advancements in technical areas such as flat panel technology may be technically feasible today but will require large capital investments for final development and production startup. If the demand is not already there, then the product should be either much better or much cheaper, or both, than the item it replaces, or it should be a new marketplace item that creates its own demand. The aircraft industry generally does not greatly influence fundamental technology (notable exceptions are aerodynamics, jet engines, materials, and control systems) because the few thousand aircraft produced per year simply cannot support the investment required. Even the automobile industry, with its several million cars produced per year, cannot influence technology as much as consumer products such as telephone systems, hand calculators, electronic games, watches, home entertainment devices, etc. Although the microelectronics industry is not currently capital intensive, the total industry resources expended have been large; they have simply been spread among many industry elements.

Commercial aviation and military and space programs have benefited greatly from Government-sponsored research and development. The technological benefits from these programs could not have been financed privately; the required resources were not available to commercial enterprise. Developments such as head-up displays, microwave landing systems, and collision avoidance systems that are being or will be implemented in new-generation aircraft are examples of such Government programs. Thus forecasting technological advances in areas that are largely Government funded is probably less risky than forecasting technological advances in microelectronics.

The technology areas assessed are data communications, data processing, actuation, and controls and displays. Sensor technology, another very important avionic function, was addressed in References 6 and 7 and therefore is not repeated here.

A more detailed summary of the technological assessment is presented in Appendix A.

5.1 DATA COMMUNICATIONS

5.1.1 INTRODUCTION

In the 1990s, it is expected that avionic and control system architectures will use multiple, distributed digital modules. These systems will be implemented using high-level languages with 32- and 16-bit processors. Data communication among the processors and the peripheral devices (i.e., sensors, actuators, displays) is the significant system link.

This section introduces two current data communication systems that are specific to aircraft: MIL-STD-1553B and the Aeronautical Radio Incorporated (ARINC) 429 data buses. Also, the Digital Autonomous Terminal Access Communication (DATAC) data bus, which is a strong contender for the 1990s-era avionic data communication system, is described. Alternative DATAC transmission media (current mode and fiber optics) are discussed in Subsection 5.1.5. These systems are compared in Reference 10 and summarized in Subsection 5.1.6.

5.1.2 MIL-STD-1553B

MIL-STD-1553B defines a high-speed, bidirectional transmission medium that has a low error rate and uses a twisted, shielded pair of conductors. As many as 31 terminals can be connected to the data bus. Each terminal can also be connected to a number of sensors and instruments. The military standard protocol carries all address data, command data, and information in serial format on a single data bus. Bus traffic is directed by the designated bus controller. This controller function can be independent of any terminal or can be colocated with selected terminals on the bus. The current version allows dynamic reassignment of the control function between appropriate terminals and monitors if a given bus controller malfunctions and has the attendant overhead penalty for this multiple terminal and controller checking, testing, and switching function. The signals on the bus are composed of address and command, data, and status words. Each word is 20 bits long and is transmitted in a serial, digital, Manchester II biphase format at a bit rate of 1 MHz. The first 3-bit time period is called the synchronizing field and is followed by 16 information bits of command, data, or status and a parity bit.

The bus controller issues command words so that information can be exchanged between (1) controller and terminal, (2) terminal and controller, (3) terminal and terminal, and (4) broadcast. The signals of the first three types of transmissions are composed of common status words and blocks of up to 32 data words, while in the fourth type, or broadcast, the controller issues a 20-bit receive command word to specific addresses and follows with a block of up to 32 data words. Only properly equipped terminals can recognize broadcast commands and receive the data.

The MIL-STD-1553B data transmission network with its distributed control capability can be very reliable and can provide a degree of adaptiveness to the avionics system. However, problems of increasing complexity and overhead burden exist when a large number of terminals, such as 100 units, are interconnected by a single bus.

5.1.3 ARINC 429

The ARINC 429 data transmission system is a relatively low-speed, high-reliability bus that typically consists of one twisted, shielded pair of conductors. Serial data transfer is unidirectional from data source to data receivers. Each data word is encoded in binary or binary-coded decimal. The data words are composed of 32 bits, including label, word type, and a parity bit. Files with 127 records or less may be transferred. Each record can have as many as 126 data words. A transmitter that is prepared to send data to a receiver will first send a "request to send" word, and the specific receiver will reply with a "clear to send" word by separate bus. Following transmission of the data, the receiver then processes the information in the transferred file data and sends a "data received OK" word back to this transmitter if there are no errors such as parity or file size. A number of protocol provisions are provided for error corrections during file transfer. Synchronization is achieved by gap width, where a minimum gap width of four bit times precedes the beginning of a new word. Two data rates are available, the high-speed 100K bps and the low-speed operation, which is within the range of 12K to 14.5K bps. One constraint is that the high and low bit-rate messages cannot be intermixed on the same bus.

5.1.4 DATAC

Development of a two-way serial transmission data bus for system avionics is consistent with the long-range goals of the airlines, as represented by ARINC. When the ARINC 429 system was conceived in the early 1970s and adopted by ARINC as a standard in the mid-1970s, it was recognized that there were many potential advantages to a multiple-access data bus. ARINC 429 simply represents the conservative first step in the evolution of a commercial transport digital data system. The DATAC data bus system could become a candidate for a second ARINC bus standard, mutually compatible with the ARINC 429 system for many years, but gradually becoming the dominant system because of its weight, cost, and reconfigurability advantages.

The DATAC data bus system can use either current mode or voltage mode (employing twisted pair) or fiber-optic mode transmission and has the following basic characteristics:

- Bidirectional, time-division-multiplexed operational protocol is used.
- Any practical number of autonomous terminals is allowed.
- All terminals are identical.
- All messages contain unambiguous data identification.
- Transmissions from a given terminal typically are of constant duration and occur periodically.
- Transmission intervals are nominally the same for all terminals on the same bus.
- Transmissions may have any planned information format provided that gaps during these transmissions are of shorter duration than those gaps separating transmissions from different terminals.

- Total duration of transmissions and gaps for all terminals on a bus must be less than the transmission interval for that bus.

- The transmission gap (i.e., the period of silence preceding any transmission of a given terminal) must be unique to that terminal.

The following protocol must be obeyed by all participating terminals:

- A terminal is in the receive mode, except when it is in the transmit mode.

- Terminal (i) transmits when the following conditions are satisfied:
  - Transmission interval T (duration since the beginning of the previous transmission by terminal (i)) has expired.
  - Transmission gap (g) has expired and the bus is still available.

Note that $T1 = T2 = T3 \ldots = Tn$ and $g1<g2<g3 \ldots <gn$.

Two protocols, A-mode and B-mode, have been developed for DATAC. Both A- and B-mode protocols are simple in concept and display adequate behavior even in the presence of bus overload resulting from a planning error. The carrier-sense feature provides the basic stimulus to the transmission-delay mechanism. Each mode has two such mechanisms: one for clash-free priority resolution and the other for voluntary transmission deferral. For both modes, each terminal has a resettable gap timer, programmable by pin selection to a unique gap time for priority resolution.

A-mode operation is characterized by periodic transmission by each terminal in the system, and B-mode operation allows terminal message durations to change continually.

Subsystem interface operation can also be controlled by the DATAC terminal on the basis of entries in the "personality" eraseable, programmable read-only memories (EPROM) within the terminal. For simple subsystems, such as sensors, actuators, etc., no other processing capability will be needed for data routing. At the other extreme, a real-time computation in a microprocessor-equipped line replaceable unit (LRU) can be served by a DATAC terminal through a shared read-write random-access memory (RAM), processor direct memory access (DMA), or by an interrupt procedure.

5.1.5 DATAC TRANSMISSION MEDIA

The two most promising transmission media for DATAC are current mode twisted-wire pairs and optical fibers. The current mode medium has highly desirable system reliability capability; fiber optics has high immunity to induced signals due to electromagnetic interference or lightning and high bandwidth capability. The choice of transmission medium in specific future applications will depend on local requirements and relative demonstrated cost, weight, and reliability.

5.1.5.1 Current Mode Bus Medium

The current mode data bus is excited, and signals on the line are sensed, by ferrite cores. Transformers are formed by inserting turns of the twisted-pair wire onto the cores. Split cores are used so that they can be inserted without cutting the line, thus maintaining integrity of the main bus.

The line can be operated to above 1 MHz. Successful operation of the main bus can be maintained even with multiple failures of cores or windings. Because split cores are used, the line is never cut. Conductive connections are needed only on the ends to properly terminate the line.

5.1.5.2 Fiber-Optic Bus Medium

Among the major advantages of fiber optics are no pickup of external electromagnetic fields, no radiofrequency interference, or crosstalk; elimination of grounds and shorts in cabling; large bandwidths for the small size; light weight; and high temperature properties. For avionic applications, single multimode, graded index fibers will probably predominate as light waveguides until gigahertz bandwidths are required or optical switching techniques become a major requirement in data processing and handling.

The connectors mating the components of a fiber-optic data bus system are the main sources of attenuation. Multiport star couplers that meet military requirements are currently being produced. Their intrinsic loss figures are at the 2-dB level, and future development is not expected to significantly improve their performance. Within a year, a fiber-optic connector suitable for avionics use will be available.

5.1.6 ARINC 429, MIL-STD-1553B, AND DATAC SYSTEM COMPARISONS

Boeing has compared the characteristics of the data bus types ARINC 429, MIL-STD-1553B, and DATAC; this comparison is contained in Reference 10.

Figure 3 illustrates a generalized installation configuration of the three candidate systems: the commercial standard, ARINC 429; the military standard, MIL-STD-1553B; and the proposed DATAC system. Figure 3 uses a rudimentary system configuration consisting of three remote devices, each requiring a number of data inputs from the other two units. The ARINC 429 system, using a separate bus for each of the data sources, would appear to provide the highest degree of independence because it is not limited to one single-channel medium. However, ARINC 429 hardware is penalized with numerous connectors and wires, high weight, and high cost. An individual receiver needs to be provided in each unit for each data source.

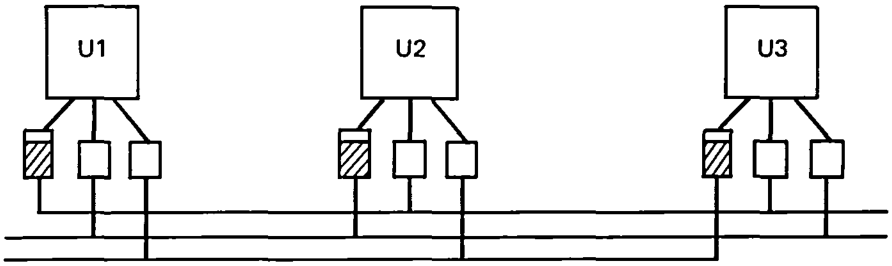
The MIL-STD-1553B system, with its distributed bus controller transfer capability, provides a degree of adaptiveness at the cost of increased complexity and overhead burden as the number of terminals increases.

The system autonomy achieved by the DATAC system approaches that of ARINC 429, in that any of the participating systems can use the data bus regardless of the operational status of any of the other systems. Furthermore, many changes in the communication requirements of a given system can be made without any effect on the programming or operation of other systems in a DATAC network. The DATAC bus—with its bidirectional, time-division-multiplexed operation, compared with the ARINC 429 characteristics—has the additional advantage of requiring significantly less hardware, such as connectors and wiring.

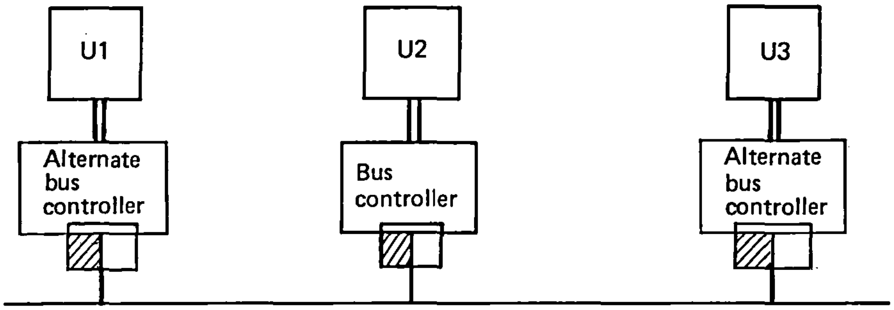
5.2 MICROPROCESSORS

The following items comprise a general consensus of the surveyed materials listed in the Appendix A references:

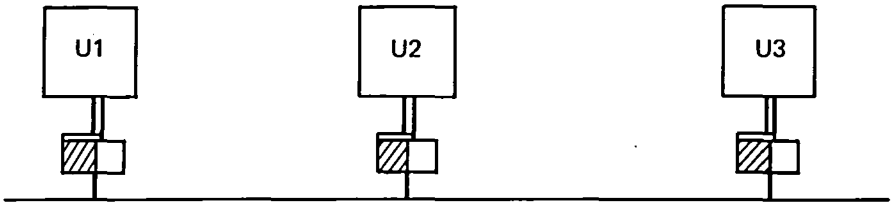
- Future avionic designs will be digital, and—with microelectronics providing the least costly hardware configurations—microprocessor and computer technology will



(a) ARINC 429



(b) MIL-STD-1553B



(c) DATAC System

Source: Reference 10.

▭ Protocol logic
▨ Transmitter
☐ Receiver

Figure 3. Physical Configurations of Candidate Data Bus Systems

become predominant. Available memory has been a limiting factor in digital electronics; but with single-chip 64K dynamic RAMs in production today and 256K to 1M bit dynamic RAMs expected in the next few years, adequate affordable memory will be available for all but a few special applications. With the increased memory on a single chip, single-chip microcomputers should grow in capability and complexity. The capability to provide high-level functions in hardware and firmware will simplify software requirements.

- Microprocessors with word lengths of 16 and 32 bits are now available and will certainly be commonplace in 2 or 3 years. These gains in microprocessor complexity and speed should reduce processing times, with chip minor cycle times of less than 20 ns. LRU major frame times of 10 to 20 ms do not appear to pose problems in the future, except for very large algorithms.

- High-level structured languages, in conjunction with 32-bit microprocessors, are expected to lead the way to increased programmer productivity, increased software reliability, and reduced software life cycle costs.

- Special applications (such as signal processing, servo control, etc.) will very likely be achieved by special-purpose, single-chip processors with onchip memory or the use of logic arrays combined with computer-aided design (CAD) techniques, thus providing the system designer with a universal, flexible component. Logic arrays of well over 10 000 uncommitted gates will be available in a year or so. To use logic arrays effectively, sophisticated design-automation technology development will be required.

- Nonvolatile memory such as magnetic bubble memories are expected to provide excellent reliability and storage densities of up to a million bits per device. Bubble memories occupy less volume than either semiconductor memories or floppy disks for the same storage capacity. Presently, bubble devices only operate over a limited temperature range and the power dissipation currently is too high; however, research continues.

5.3 ACTUATORS AND ACTUATOR CONTROLLERS

Actuators provide power for flight controls, engine controls, thrust reversing, landing gear retraction and extension, nose-wheel steering, brakes, wheel well doors, and other functions on commercial transports. Most of these functions presently use hydraulic actuators. However, recent high-efficiency electric motor and control developments may make electromagnetic actuators competitive with hydraulic actuators in this decade.

In the near term, commercial transport designers will usually use more-or-less conventional hydraulic systems for flight-crucial controls (subsec 6.2.2) because all-electric surface controls have not yet been developed that can perform the required functions with competitive advantages in weight and reliability. However, all-electric control functions have been used on current new-generation commercial transports; e.g., the Boeing 757 is planning to use a full-authority electronic engine control on the Pratt & Whitney 2037 engine, with no mechanical or hydraulic system backup. Airplane actuator technological development is focused on achieving benefits in weight, design flexibility, reliability, and maintainability. Some of these technology objectives could result from efforts outside the airplane industry; e.g., as industries (such as automobile manufacturing) become more automated, reliability of the robotized production lines will become an important consideration and there will be more incentive to develop improved actuator components.

Currently, on a system component basis, electric actuators still weigh from 10% to 30% more than their hydromechanical counterparts. When the hydraulic power and distribution system is included, a closer weight parity may be achieved. As developments in load-adaptive actuators evolve (both electric and hydraulic), significant weight reductions will be achieved. The principal benefits expected from electric actuation systems will be design flexibility and simplified maintenance. Integrated actuator packages (IAP) and electromechanical actuators are expected to become dominant in the 1990s for commercial transport applications.

5.4 FLIGHT DECK CONTROLS AND DISPLAYS

Design of the flight deck—the operator-machine interface—is achieved under a nearly fixed set of constraints that is dictated by the form and functional limits of the human operators. Those changes that occur in the operator-imposed constraints involve more precise definition, not improved inherent operator capacity to perform his functions.

In contrast to the fixed capacities of the operator, increasing airplane system complexities—together with the requirement for the operator to monitor, interpret, and react to an expanding bevy of parameters—eventually resulted in a requirement for multiparameter controls and displays to reduce the congestion and workload inherent with single- or double-parameter display, test, and control devices. Multifunction keyboards and displays were developed, suited to flight deck operational requirements. Electromechanical instruments of the kind used since the 1920s, however, are still incorporated into the flight decks of commercial aircraft flying in the 1980s. And some of these instruments may still be required in the 1990 ACT airplane as analog backup for functions and parameters of flight-crucial significance for which a satisfactory all-electronic redundancy scheme cannot be practically achieved.

The 1990 ACT airplane flight deck will be fully integrated, all-electronic fly by wire based on digital avionics. New cockpit controls and displays being developed in 1980 to 1990 will be ready for installation in the next-generation transport.

It is predicted that multicolor cathode-ray tubes (CRT) will continue to dominate the market for use in cockpit display of imagery. The requirement to display weather radar, forward-looking infrared (FLIR) radar, and TV video on the electronic attitude director indicator (EADI) and electronic horizontal situation indicator (EHSI) presents a challenge to flat panel technology that may not be met by 1990. Flat panels are expected to be rugged, to have a low packaging profile and high luminous efficiency, to be highly reliable, and to make good progress in the next decade. However, it is not certain that they can overcome the longer history and certain advantages of the CRT (table 6) in the near term. For display of sensor video (TV, FLIR, radar) on the EADI and EHSI, color CRTs will dominate the market throughout the 1980s. A flat panel display with the best chance of replacing CRTs in the next few years is probably electroluminescence (EL), specifically thin-film EL (TFEL).

Table 6. Summary—Display Technology Comparison Matrix

Characteristic	Desired	CRT	EL (thin film)	LC	LED	Plasma
Common sizes	15 x 20 cm (6 x 8 in) <2.5-cm (<1-in) depth	13 x 18 cm (5 x 7 in) (usable) <36-cm (<14-in) depth	13 x 15 cm (5 x 6 in) <2.5-cm (<1-in) depth	9 x 9 cm (3.5 x 3.5 in) <2.5-cm (<1-in) depth	10 x 13 cm (4 x 5 in) <2.5-cm (<1-in) depth	21.5 x 21.5 cm (8.5 x 8.5 in) <2.5-cm (<1-in) depth
Luminance (filtered)	50 to 100	4.6 to 44 raster 25 to 300 stroke (B-R-G)	40	Illumination dependent	120	20 to 50: ac 0 to 50: dc
Shades of gray at 108 000 lx (10 000 fc)	6 to 8	6 to 8	2 (16 predicted)	8 to 10	4 to 6	ac: 2 dc > 16
Contrast ratio at 108 000 lx (10 000 fc)	7.5:1 HDD 1.2:1 HUD	4:1 color 12:1 monochromatic	1.5:1 (10:1 predicted)	20:1 at 60°C (+140°F) 2:1 at 0°C (+32°F)	6:1	1.6:1
Colors	8 to 16	> 20	2 to 3 (B-G-Y) (full color predicted)	1 normally (3 predicted) (R-G-Y)	4 (R-O-Y-G)	1 green 1 neon orange Full color using UV predicted
Resolution, lines/cm (lines/in)	26 to 40 (65 to 100)	32-dot triad per centimeter (80-dot triad per inch)	20 (50) 26 to 80 (65 to 200) predicted	40 (100) reflective 24 (60) transmissive	25 (64) monochromatic 9 (23) (R-G)	24 to 35 (60 to 88)
Refresh rate, Hz	50 to 100	50 stroke 40/80 raster	60 to 250	Slow (TV rate blurred)	500 (typical)	None (bistable)
Rise or fall response	TV rate (0.2 μs)	0.2 μs to 1 ms	2 μs to 1 ms	10 ms to 1 sec	10 ns	20 μs
Operating temperature, °C (°F)	-55 to +125 (-67 to +257)	-20 to +70 (-4 to +158)	-40 to +100 (-40 to +212)	-25 to +60 (-14 to +140)	-40 to +70 (-40 to +158)	-60 to +60 (-76 to +140)
Voltage and power	115V ac, 400 Hz	> 18 kV 0.78 W/cm^2 (5 W/in^2) (typical)	30V to 650V ac 0.125 W/cm^2 (0.8 W/in^2) (typical)	2V to 35V dc 0.031 W/cm^2 (0.2 W/in^2) (average)	1.5V to 5.0V dc 3 W/cm^2 (20 W/in^2) (typical)	140V sustain 200V firing 0.47 W/cm^2 (3 W/in^2) (typical)

Table 6. Summary—Display Technology Comparison Matrix (Concluded)

Characteristic	Desired	CRT	EL (thin film)	LC	LED	Plasma
Luminous efficiency, lm/W	Maximum	20 (typical)	2 to 5 (typical)	N/A	0.5 (typical)	0.3 (DIGIVUE)
Dominant wavelength	555 nm	Varies with phosphor type	525 to 585	Varies	470 to 650	585 (neon)
MTBF (high ambient)	> 10 000 hr	3000 to 5000 hr (10 000 hr predicted)	10 000 hr (20 000 hr reported)	10 000 hr (20 000 hr predicted)	10 000 hr (25 000 hr predicted)	> 10 000 hr
Viewing angle	±60 deg (minimum)	±80 deg	±90 deg	±15 to ±40 deg	± 45 deg	±70 deg
Readability (high/dark)	Excellent / Excellent	Excellent / Excellent	Marginal / Excellent	Excellent / Poor	Good / Good	Marginal / Poor
Cost	Minimum	• $4700 commercial • $15 750 flight quality	• $3500 to $5000 • Nonflight quality	Unknown (no production quantities)	• $6500 nonflight quality • \$620/cm^2 (\$4000/in^2) with drivers	• $4000 to $9500 • Nonflight quality
Devices recommended (1980/1990)	• Video • Graphics • Messages • Discretes	• Video • Graphics • Messages • Discretes	• Messages • Discretes	• Messages • Discretes	• Graphics • Messages • Discretes	• Graphics • Messages • Discretes
		• 1990— same as above	• Video • Graphics • Messages • Discretes	• Graphics • Messages • Discretes	• Graphics • Messages • Discretes	• Graphics • Messages • Discretes

For display of graphics, alphanumeric messages, and discretes, it is predicted that any one of the flat panel technologies can perform adequately. During 1980-85, light-emitting diodes (LED) will lead the field in cockpit applications, especially for the Traffic Alert and Collision Avoidance System (TCAS), Mode-S, ARINC communication addressing and reporting system (ACARS), and multifunction keyboard (MFK) displays. But because of high power consumption, cooling requirements, and cost, they will yield to the more efficient TFEL, which uses only 1/20th the power of LED, has twice the viewing angle, and is many times more light efficient than LED.

An improved flight management system will integrate 4-D navigation, communication, guidance, and performance (including energy) management functions, optimized for fuel savings within air traffic control (ATC) constraints. Present keyboards will be replaced with MFKs for manual data entry, recall, and modification of stored data. Data presented to the crew will consist of a logical and meaningful sequence of displayed "pages" and will prevent insertion of incompatible options. Flight plans and bulk data storage will be automatically inserted with cards and tapes, respectively. Route changes and verification of flight plans will be integrated with Mode-S. Voice-actuated controls will allow communication with the flight management system, perhaps as the primary input device with the MFK.

Low-profile throttles and center stick control will open up the prime display area. Electronic throttles, elevator trim, and flap controls will make available more panel space on the forward instrument panel for display of Mode-S messages. A center stick would unblock the display area for EHSIs, an area now partly obstructed by the traditional wheel and column.

By replacing standard electromechanical (or even CRT) engine instruments, thin flat panel displays, less than 2.5 cm (1 in) deep, will provide additional space behind the glareshield for installation of holographic head-up display (HHUD) relay optics and projection electronics. Symbolic information will be projected onto large HHUD combiners or perhaps even on the windscreen, in all probability with liquid-crystal (LC) transmissive projection systems.

Most of the system controls and displays on the overhead panel will disappear with the advent of MFK and multifunction displays (MFD). If needed, graphics and alphanumeric information can be shown on displays located on the forward main instrument panel.

The primary flight displays will be full-color CRT, multifunctional, interchangeable, and compatible with ARINC standard racks and panels for common insertion and removal. The flat panel displays for engines and systems will be full color, multifunctional, and ARINC compatible. By 1995, it is predicted that all of these displays will be flat panel and standardized for interchangeability. The other smaller displays used for instruments, caution and warning, navigation, communications, and keyboard readout devices will be flat panel, full color, standard width, and interchangeable.

6.0 ACT AVIONICS AND FLIGHT DECK SYSTEM FUNCTION DEFINITION

The objective of this effort was to define integration of the active control functions into an integrated avionics system. The system was to be defined at a level appropriate for simulation of the integration concept. Because the focus of the effort is integration of active controls, the scope of the study was limited to those other functions affected by or that affect the active control functions. Therefore only the functions involved in active controls, normal flight control, and guidance were considered in the detailed portions of the study. Figure 4 shows the approach taken to develop the integrated system.

Many of the concepts and guidelines presented in References 11 through 16 were used in the development and analysis work discussed in this section and in Section 7.0.

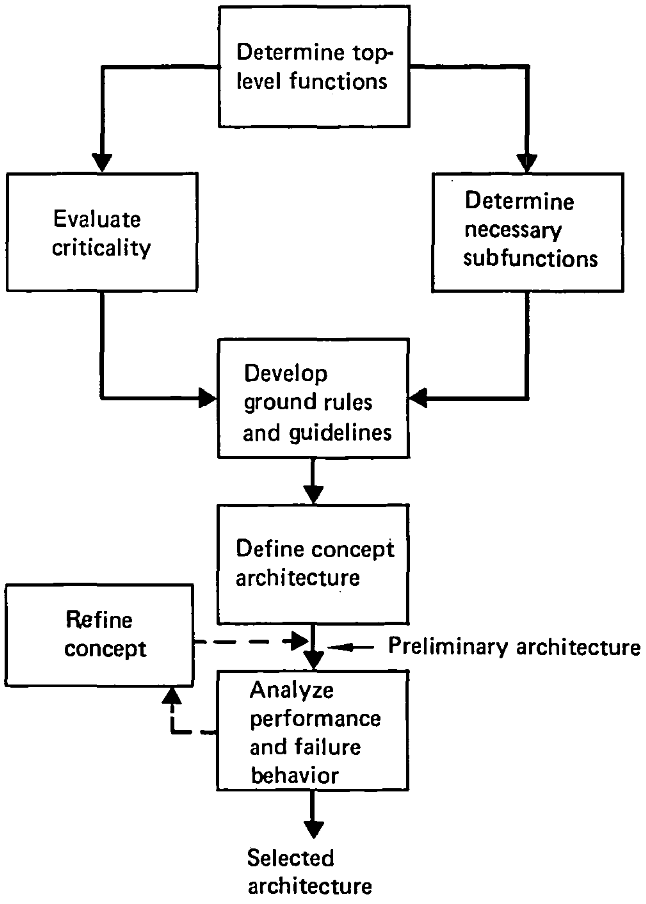


Figure 4. Development Approach

The first step then was to define top-level functions expected to be performed by the 1990s airplane avionics system. The top-level function list was developed by reviewing the functions performed on current aircraft, functions defined in the Aeronautical Radio Incorporated (ARINC) 700 series documentation, and airborne functions due to be added because of the changing operational environment, including the Active Controls Technology (ACT) functions. Subsection 6.1 presents the resulting top-level functions, except electric power, environmental control, and passenger accommodations. (Many of the monitor and alert functions are listed for those excluded functions.)

The second step was to evaluate the criticality of the top-level functions. The purpose of the development approach was to introduce reliability considerations early in the design process. To do this, criticality "ratings" are determined that reflect the impact on safety or operations of the loss of the top-level functions. These criticality "ratings" are used as guidelines for high-level grouping and interconnections of the concept architecture. Subsection 6.2 discusses determination of criticality.

The third step was to define the subfunctions or processes necessary to perform the top-level functions. Data processing techniques were used to identify these processes. Specifically, data flow diagrams were sequentially generated illustrating the top-level functions in progressively more detail. In this way, subprocesses were determined on a level suitable for allocation to elements in the concept architecture. Subsection 6.3 discusses these data flow diagrams or logical function groupings.

6.1 AIRPLANE CONTROL, MONITOR, AND DISPLAY FUNCTIONS

The top-level functional list consists of two sections, as shown in Table 7. Section 1.0 identifies the functions necessary for revenue flight operations. Section 2.0 shows those functions that are normally related to relief of aircrew workload or that allow more economical flight operations.

Table 7. Top-Level Functional List

Function number	Function description
1.0	Basic capabilities
1.1	Control and stabilize airplane attitude
1.1.1	Change pitch attitude via column deflections
1.1.2	Adjust pitch attitude trim
1.1.3	Change roll attitude via wheel deflections
1.1.4	Adjust roll attitude trim
1.1.5	Change side-slip angle via rudder deflections
1.1.6	Adjust yaw trim
1.1.7	Change control authority (or trim) as a function of flight conditions to maintain flight characteristics (e.g., rudder ratio changer, outboard aileron lockout, elevator feel, Mach speed trim)
1.1.7.1	Modify pitch control characteristics
1.1.7.2	Modify roll control characteristics
1.1.7.3	Modify yaw control characteristics
1.1.8	Augment stability
1.1.8.1	Pitch axis, short
1.1.8.2	Pitch axis, speed
1.1.8.3	Roll-yaw axis (LAS)
1.1.9	Limit angle of attack (AAL)
1.2	Relieve structural loads
1.2.1	Maneuver-load control
1.2.2	Gust-load alleviation
1.2.3	Flutter-mode control
1.3	Control and stabilize airplane thrust axis
1.3.1	Change engine thrust as a function of throttle position
1.3.2	Deploy speedbrakes as a function of speedbrake lever position
1.4	Change airplane configuration for phase of flight
1.4.1	Landing gear
1.4.2	Flaps
1.5	Monitor airplane status
1.5.1	Flight conditions, display
1.5.1.1	Altitude
1.5.1.2	Vertical speed
1.5.1.3	Attitude, pitch, and roll
1.5.1.4	Engine thrust
1.5.1.5	Direction (heading and track)
1.5.1.6	Turn rate
1.5.1.7	Time
1.5.2	System status, display system performance (e.g., engine, hydraulics, electrical)
1.5.3	Navigation and guidance display bearing and/or distance to navigation aids; display deviation from selected landing system path
1.5.4	Communications
1.5.4.1	Air to ground and ground to air
1.5.4.1.1	Voice
1.5.4.1.1.1	ATC and company
1.5.4.1.1.2	Automatic terminal information service (ATIS)
1.5.4.1.2	Transponder
1.5.4.2	Intracraft
2.0	Enhanced capabilities
2.1	Engage automatic flight control
2.1.1	Pilot-assisted steering
2.1.2	Capture and maintain flight parameters (thrust, speed and Mach No., heading and track, etc.)
2.1.3	Capture and track landing system path (ILS, MLS, etc.)
2.2	Use autonavigation and guidance
2.2.1	Define and store complete flight plan
2.2.2	Define and store the desired performance modes that specify the optimal profile(s) (cost, fuel, time)
2.2.3	Determine airplane state (position, velocity)
2.2.4	Provide flight parameter targets to follow optimal flight profile
2.3	Monitor information displays
2.3.1	Display autoflight pitch, roll, airspeed, and thrust commands
2.3.2	Display selected thrust limits
2.3.3	Display desired flight profile
2.3.4	Display airplane state (position, velocity)
2.3.5	Display aeronautical chart data
2.3.6	Display performance handbook data (including ACT failure envelope)
2.4	Monitor crew alerts
2.4.1	Flight condition alerts
2.4.1.1	Overspeed
2.4.1.2	Improper configuration
2.4.1.3	Fire warning
2.4.1.4	Autopilot disconnect
2.4.1.5	Ground proximity
2.4.1.6	ACT system
2.4.2	System status alerts
2.4.2.1	Air-conditioning
2.4.2.2	AFCS
2.4.2.3	Electrical power
2.4.2.4	Fire protection
2.4.2.5	Flight control
2.4.2.6	Fuel
2.4.2.7	Hydraulic power
2.4.2.8	Ice and rain protection
2.4.2.9	Instruments
2.4.2.10	Landing gear
2.4.2.11	Navigation
2.4.2.12	Pneumatics
2.4.2.13	Auxiliary power unit
2.4.2.14	Doors
2.4.2.15	Engine control
2.4.2.16	Anti-ice
2.4.2.17	Engine indication
2.4.2.18	Oil

6.2 CRITICALITY DETERMINATION

Future airplanes using ACT will have new systems whose continuous function is necessary for continued safe flight. Other airplane systems enhance performance in some flight regimes but may not be flight safety critical if airplane operation is limited to a restricted flight envelope when a system malfunction is known to have occurred. Thus one of the first steps in defining system requirements is to examine the flight safety significance of the system functions. The resulting function criticality indicates the minimum level of design verification and validation necessary and the reliability required of each individual function. The assessment is achieved by determining the impact of function loss on flight safety.

6.2.1 CRITICALITY ASSESSMENT TECHNIQUES

Three levels of flight criticality (flight crucial, flight critical, and workload relief) are used to categorize the functions—related by their criticality, implementation, and usage in a particular type or model. Another category (dispatch critical) is also included to show which functions must be operational before an airplane can fly a revenue mission. Table 8 defines each criticality category and the associated reliability requirements.

The criticality assessment process includes four basic steps:

- Clearly defines the capabilities of the function
- Determines the consequences on safety and/or condition of flight of loss of these capabilities
- Assigns functions to criticality category by selecting the most appropriate category from Table 8 that possesses similar characteristics and behavior
- Determines whether the airplane can be dispatched with function loss

Finally, function reliability requirements are derived by considering the worst possible impact to flightcrew and airplane on function loss and then looking up the corresponding failure probability as indicated by the curve in Figure 5. Table 9 shows a typical criticality assessment sheet.

Table 8. Function Criticality Categorization

Category		Effect of function failure or design error on the airplane and crew	Probability of occurrence per 1-hr flight		Remarks
			FAA definition	Unofficial interpretation [a]	
A	Flight crucial	That function whose complete loss inevitably results in loss of the airplane. The consequence of complete function loss cannot be averted by procedure change or flight envelope restriction.	Extremely improbable	$< 10^{-9}$	
B	Flight critical	That function whose complete loss in a specific portion of flight could result in loss of the airplane, but such loss could be averted by proper flightcrew action.	Probable to improbable	10^{-3} to 10^{-9}	Includes: • Flight envelope critical—a function that if lost results in certain airplane regimes being restricted or results in hazardous increase in flightcrew workload. • Flight missions critical—a function that if lost results in certain airplane operations being prohibited or results in potentially hazardous increase in flightcrew workload. [b]
C	Workload relief	That function that impacts neither flight dispatch status nor flight plan but that has convenience value to flightcrews. Loss of function may affect precision or economy of flight but has no significant effect on safety.	Probable	[c]	
D	Dispatch critical	That function without which an airplane cannot legally be dispatched on a revenue flight.	Not applicable	$<$ 0.65 delays over 15 min per 1000 departures	Meets minimum requirement [d]

[a] These terms are not intended to define the reliability of specific components of systems but rather to relate to the effects on the airplane of a single consequence resulting from the loss of a function or functions. The numerical limits are not precise values and judgment should be used in their application. This is reflected in the overlap of the limits shown in Figure 5.

[b] Failure of a single function in this category causes at least "operational limitation." Failure of several functions simultaneously, however, may require an immediate diversion to a landing on the nearest adequate runway.

[c] This depends more on economic factors such as cost and weight rather than safety factors.

[d] The minimum requirement is that necessary to provide compliance to (1) regulatory requirements (such as FARs) not associated with the probability ranges and/or to (2) applicable TSO or other equipment requirements.

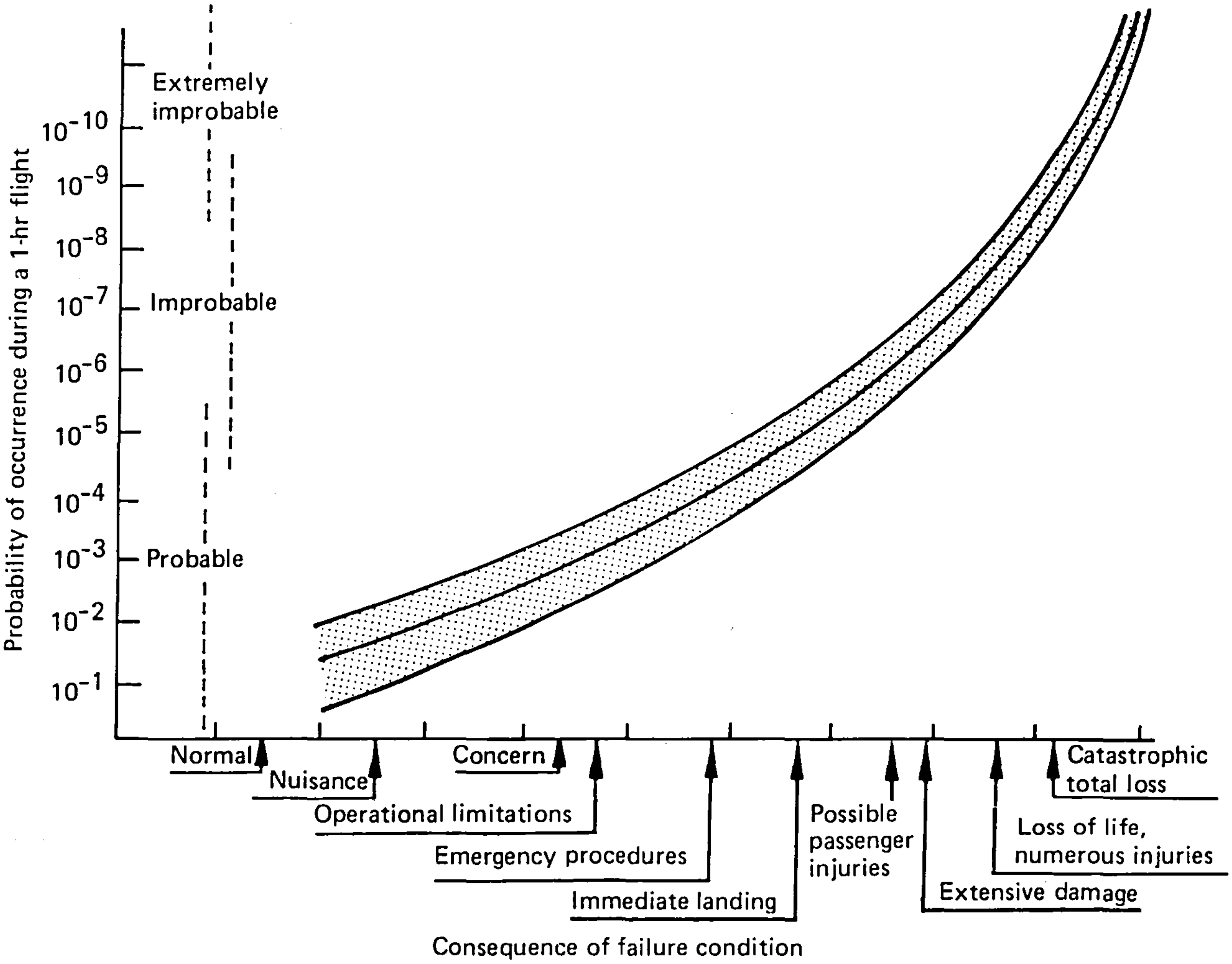


Figure 5. Relationship Between the Consequence of Failure and the Probability of Occurrence

Table 9. Function Criticality Assessment

<table>
<tr><td>Function</td><td colspan="2">Gust-load alleviation (GLA)</td></tr>
<tr><td>Brief description</td><td colspan="2">Consequence of failure</td></tr>
<tr><td>● Reduces the wing structure loading that results from the airplane penetrating vertical (or lateral) gusts</td><td colspan="2">● Unable to control gust-load onset through deflections of wing controls and to pitch the airplane into the gust through commands to the elevators
● Unable to reduce structural loading at low, rigid-body frequencies
● Allows continuation of normal flight schedule after GLA is lost in the air because the airplane structure ultimate strength exceeds the design limit load
● Cannot be dispatched on ground because the airplane structural strength is less than the design ultimate load at maximum gross weight</td></tr>
<tr><td>Flight criticality</td><td>Critical (B)*, 10^{-3} to 10^{-4}</td><td rowspan="2">Remarks:</td></tr>
<tr><td>Dispatch criticality</td><td>Yes</td></tr>
</table>

*See Table 8 for definition of category B.

Some top-level functions have a different impact on safety of flight or ability to complete the scheduled mission depending on the phase of flight (takeoff, climb, cruise, etc.), flight environment (night, weather, icing, etc.), or route (over water, positive radar control, radio navigation aid availability, etc.). Some functions are used only in certain phases of flight or over certain flight routes, while others have a significant safety effect only if they fail in certain environmental conditions. For these functions, the likelihood of the conditions must be considered along with the condition-dependent effect of the function loss. In this study, most of the functions with condition-dependent effects appear in the flight critical category.

6.2.2 ACT SYSTEM CRITICALITY ASSESSMENTS

The criticality assessments cover the top-level ACT/control/guidance functions selected from the function list in Table 7. Table 10 lists assigned criticality category, minimum reliability requirements, and demonstrated past dispatch reliability for these selected functions.

Appendix B contains more detailed criticality assessment data for each of the top-level functions.

Table 10. Function Criticality

Function	Flight criticality	Permissible failure probability per 1-hr flight	Dispatch critical?	Demonstrated past dispatch reliability
Change pitch attitude via column deflections	Crucial	$< 10^{-9}$	Yes	–
Adjust pitch attitude trim	Critical	$< 10^{-4}$	Yes	10^{-5} to 10^{-6}
Change roll attitude via wheel deflection	Crucial	$< 10^{-9}$	Yes	–
Adjust roll attitude trim	Workload relief	10^{-3}	Yes	10^{-5} to 10^{-6}
Change side-slip angle via rudder deflection	Critical	$< 10^{-7}$	Yes	10^{-5} to 10^{-6}
Modify pitch control characteristics	Critical	10^{-3} to 10^{-4}	Yes	10^{-5} to 10^{-6}
Modify roll control characteristics	Critical	10^{-3} to 10^{-4}	Yes	10^{-5} to 10^{-6}
Modify yaw control characteristics	Critical	10^{-3} to 10^{-4}	Yes	10^{-5} to 10^{-6}
Augment short-period mode pitch axis stability	Crucial	$< 10^{-9}$	Yes	–
Augment speed mode pitch axis stability	Critical	10^{-3} to 10^{-4}	Yes	–
Augment roll-yaw axis stability (LAS)	Critical	10^{-3} to 10^{-4}	Yes	–
Limit angle of attack	Critical	$< 10^{-4}$	Yes	10^{-5} to 10^{-6}
Maneuver-load control	Critical	10^{-3} to 10^{-4}	Yes	–
Gust-load alleviation	Critical	10^{-3} to 10^{-4}	Yes	–

Table 10. Function Criticality (Continued)

Function	Flight criticality	Permissible failure probability per 1-hr flight	Dispatch critical?	Demonstrated past dispatch reliability
Flutter-mode control	Critical	10^{-3} to 10^{-4}	No	–
Display airspeed and Mach	Critical	10^{-6} to 10^{-9}	Yes	10^{-4} to 10^{-6}
Display altitude	Critical	$< 10^{-5}$	Yes	10^{-4} to 10^{-6}
Display vertical speed	Critical	$< 10^{-4}$	No	–
Display attitude, pitch, and roll	Critical	$< 10^{-5}$	Yes	10^{-3} to 10^{-5}
Display engine thrust	Workload relief	10^{-3}	Yes	–
Display direction (heading, track)	Critical	$< 10^{-5}$	Yes	10^{-5} to 10^{-6}
Display bearing and/or distance to navigation aids	Critical	10^{-3} to 10^{-4}	Yes	10^{-3} to 10^{-5}
Display deviation from selected landing system path	Critical	10^{-3} to 10^{-4}	Yes	–
Communications with voice	Critical	10^{-3} to 10^{-4}	Yes	10^{-3} to 10^{-5}
Communications with transponder	Workload relief	10^{-3}	Yes	10^{-4} to 10^{-6}
Pilot-assisted steering	Workload relief	10^{-3}	No	–
Capture and maintain flight parameters	Workload relief	10^{-3}	No	–
Capture and track landing system path	Critical	$< 10^{-4}$	Yes	$\approx 10^{-4}$

Table 10. Function Criticality (Concluded)

Function	Flight criticality	Permissible failure probability per 1-hr flight	Dispatch critical?	Demonstrated past dispatch reliability
Determine airplane state (position, velocity)	Workload relief	10^{-3}	No	–
Provide flight parameter targets to follow optimal flight profile	Workload relief	10^{-3}	No	–
Display selected thrust limits	Workload relief	10^{-3}	No	–
Display desired flight profile	Workload relief	10^{-3}	No	–
Display airplane state (position, velocity)	Workload relief	10^{-3}	No	–
Display performance handbook data (include ACT failure envelope)	Workload relief	10^{-3}	No	–
Display autoflight pitch, airspeed, roll, and thrust command	Workload relief	10^{-3}	No	–
ACT system flight condition alerts	Crucial Critical	10^{-9} $< 10^{-5}$	Yes	–
Flight control system status alerts	Critical	$< 10^{-5}$	Yes	–

6.3 LOGICAL FUNCTION GROUPING

Lists of top-down-ordered functions, such as shown in Table 7, are too complex to use alone as system design tools. For this reason, some of the techniques from structured analysis have been adopted. Structured analysis provides an orderly procedure for presenting system functional relationships, with significant data flow also delineated.

The first stage of the procedure begins by developing a model of the current physical system showing the physical processes that are involved. Next, the current physical model is rearranged and expanded in a logical sequence using the generalized system functions. From the logical model, the alternative configurations can be identified. After selecting a suitable configuration, the significant areas of change for the proposed system can be identified. Finally, the proposed physical system can be diagrammed and structured specifications prepared.

The principal method used to develop the data flow diagrams, with their functional groupings, was based on DeMarco's approach (ref 11). This graphical method enhances understanding of the data flow, which is vital to any system design. The method does not guarantee that the optimum design will result, but, if used properly, a logical or workable system will be developed.

The primary elements of the diagrams are the interconnecting paths (data flow) and the "bubbles" (processes). The highest level diagrams would show the entire airplane avionic system from which groups of the elements can be selected to develop lower level, more detailed diagrams. It is the selection of the groupings that may seem arbitrary; selection may be based upon similarity of function, equal criticality, proximate physical location, etc. The flight control and ACT functions were grouped by criticality, thereby ensuring that lower criticality subsystems could not affect those of higher criticality. (For systems of lower criticality, it may make sense to group selections on another basis.) Once this grouping selection decision is made, development of the data flow diagram is almost automatic because the choices are so constrained.

Data flow diagrams accomplish two important things. The first is a meaningful picture of the system; as a byproduct of this picture, a highly useful system functional partitioning is presented. The later physical partitioning that is done will relate directly to this functional partitioning.

The second major feature of graphic functional modeling is that it can be used directly in existing computerized modeling programs. Thus, complicated system trades can be conducted at the functional level, before committing to a physical system design. Computerized modeling was not necessary to successfully accomplish the task described herein; because of the ground rules and assumptions in Subsection 7.3, functional partitioning of the systems studied in detail was nearly automatic. If an airplane and airplane system were to be designed from the ground up, with no preconceived architectural rules, computerized functional modeling could prove to be very advantageous.

The final structured specifications mentioned previously include data flow diagrams, data dictionary, and process descriptions. A data dictionary describes components and addresses redundancy questions using self-defining terms and easily understandable names. The process description is a minispecification that clarifies the identified functions.

A high-level data flow diagram that illustrates the entire system showing the external interactions is called a context diagram. With this type of diagram, the major functions of the system and how they interrelate can be seen easily. Figure 6 shows the context diagram for the ACT system.

The context diagram shows distribution of pilot inputs to high-level function groups. Data flow is indicated by the arrowed lines connecting the circles that contain the process functions. The high-level functions of the functions list appear in the context diagram along with the indicated data flow.

The following major functional separations are indicated by the six shaded regions on the context diagram:

- Region 1: information displays, status displays, and crew alerts
- Region 2: autoflight systems, including autonavigation, guidance, and control functions
- Region 3: thrust axis control
- Region 4: airplane configuration changes for various flight phases

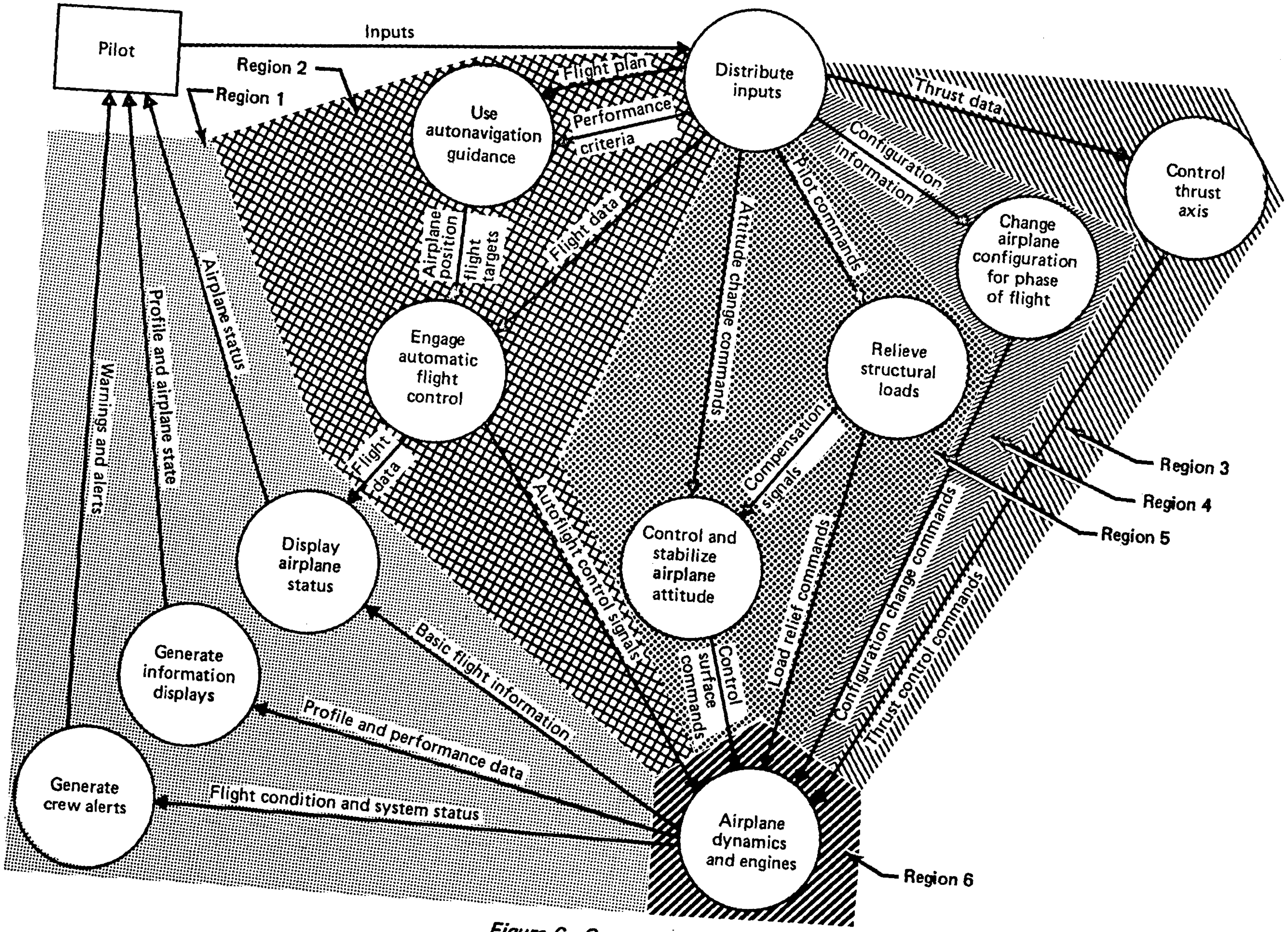


Figure 6. Context Diagram

- Region 5: attitude control and stabilization plus structural load relief

- Region 6: interconnecting of the major functions controlling airplane dynamics

Status feedback from the various airplane systems flows to the pilot through displays and alerts. Mechanical feedback (e.g., stick shaker) remains within the appropriate function group of the data flow diagram. The following functional grouping has been selected:

- The crucial and primary control related functions are within the same group.

- Control of thrust axis, which deals with speedbrakes and engine thrust, is a separate group.

- Airplane, phase of flight, and configuration functions are a group.

- Autonavigation and guidance, plus the automatic flight control functions, are considered to be workload relief functions and are expected to have a high level of integration.

- Information and status displays, including alerts, form a single group.

Figure 7 shows the data flow diagram illustrating the thrust axis control (3)*; Figure 8 contains the airplane configuration changes for various flight phases (4)*; and Figure 9 lists the autoflight systems, including autonavigation, guidance, and control functions (2)*. Figure 10 gives details of attitude control and stabilization plus the structural load relief functions (5)*.

As shown in Figure 10, the pilot provides input via the column, wheel, and pedal deflections, etc., which, in conjunction with sensor input information, perform the indicated functions to generate the appropriate control surface signals.

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*These are the numbered regions on the context diagram (fig. 6).

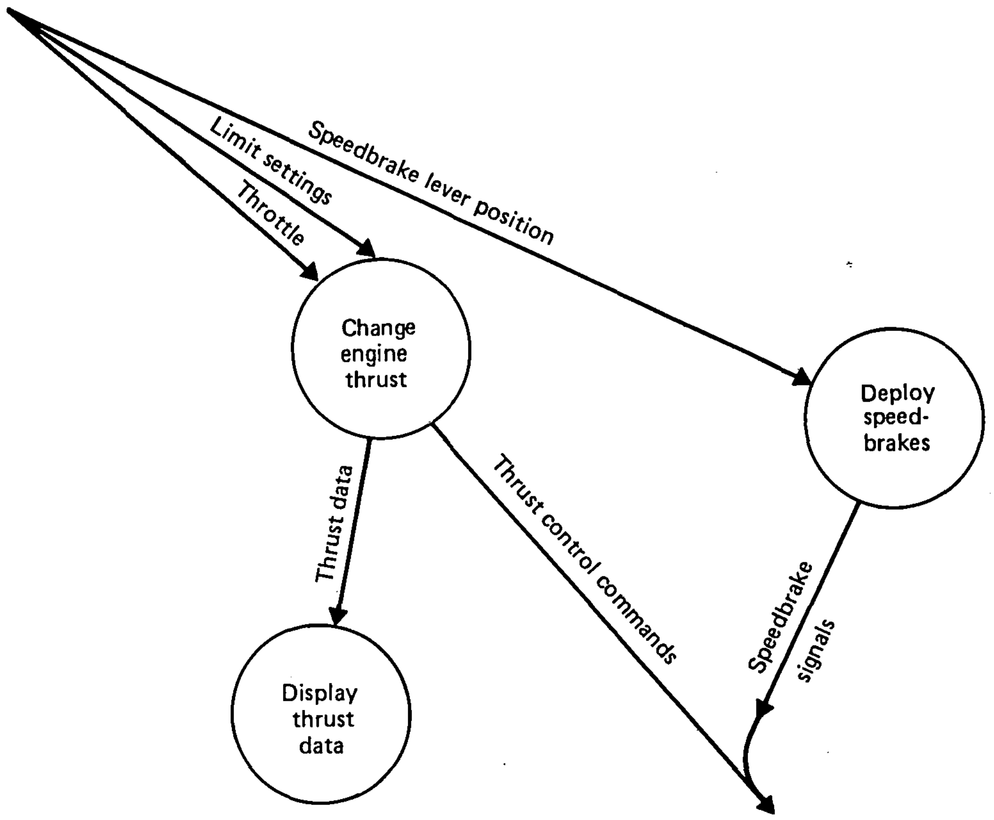


Figure 7. Thrust Axis Control

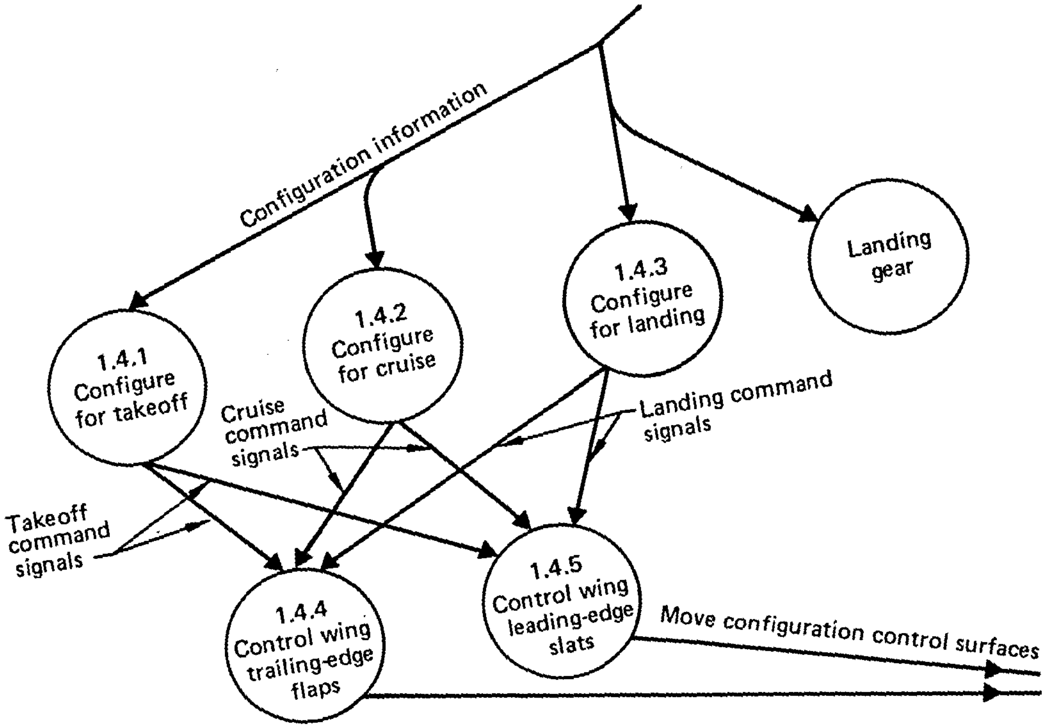


Figure 8. Airplane Configuration Changes for Phase of Flight

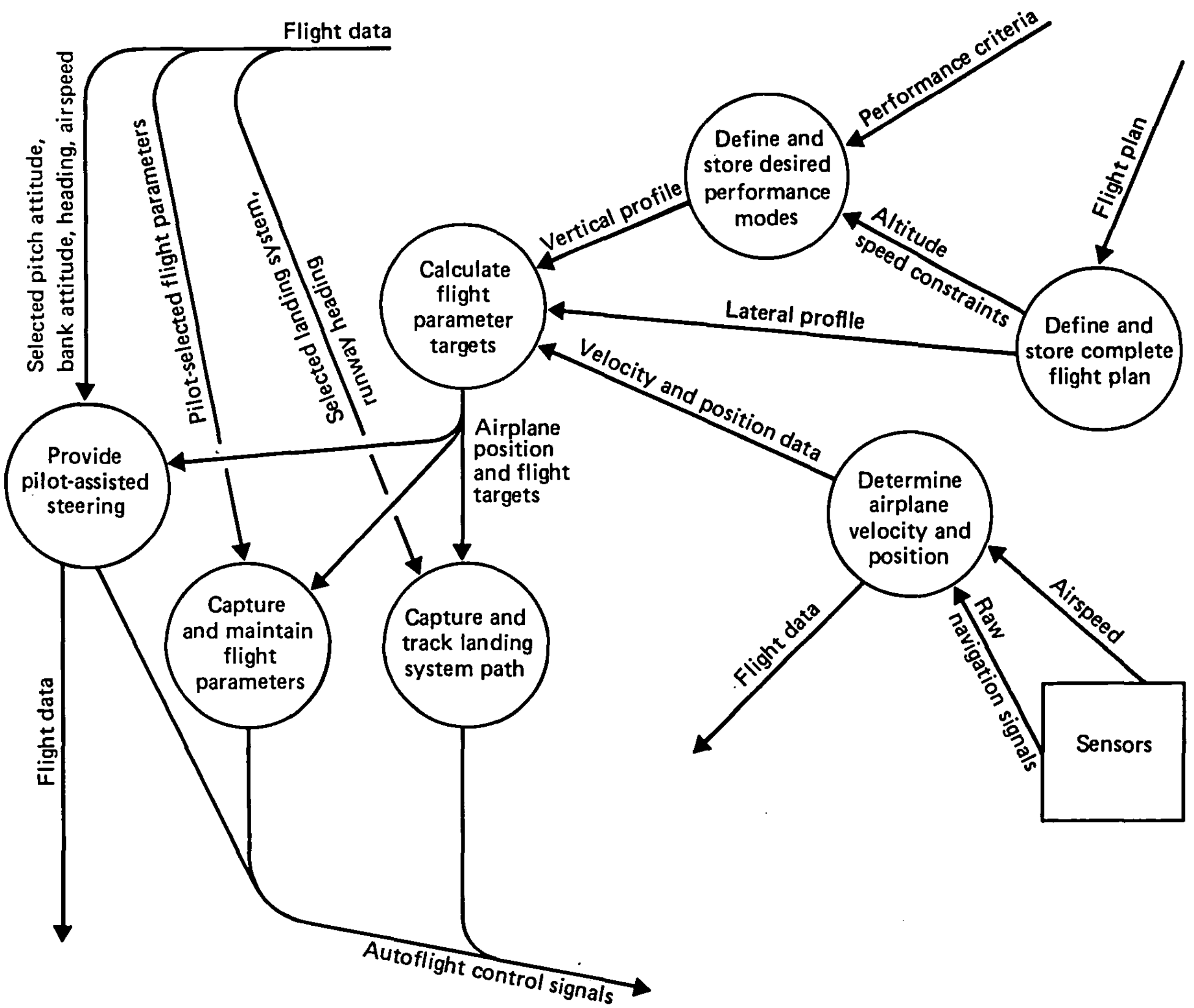


Figure 9. Autonavigation, Guidance, and Autoflight Control

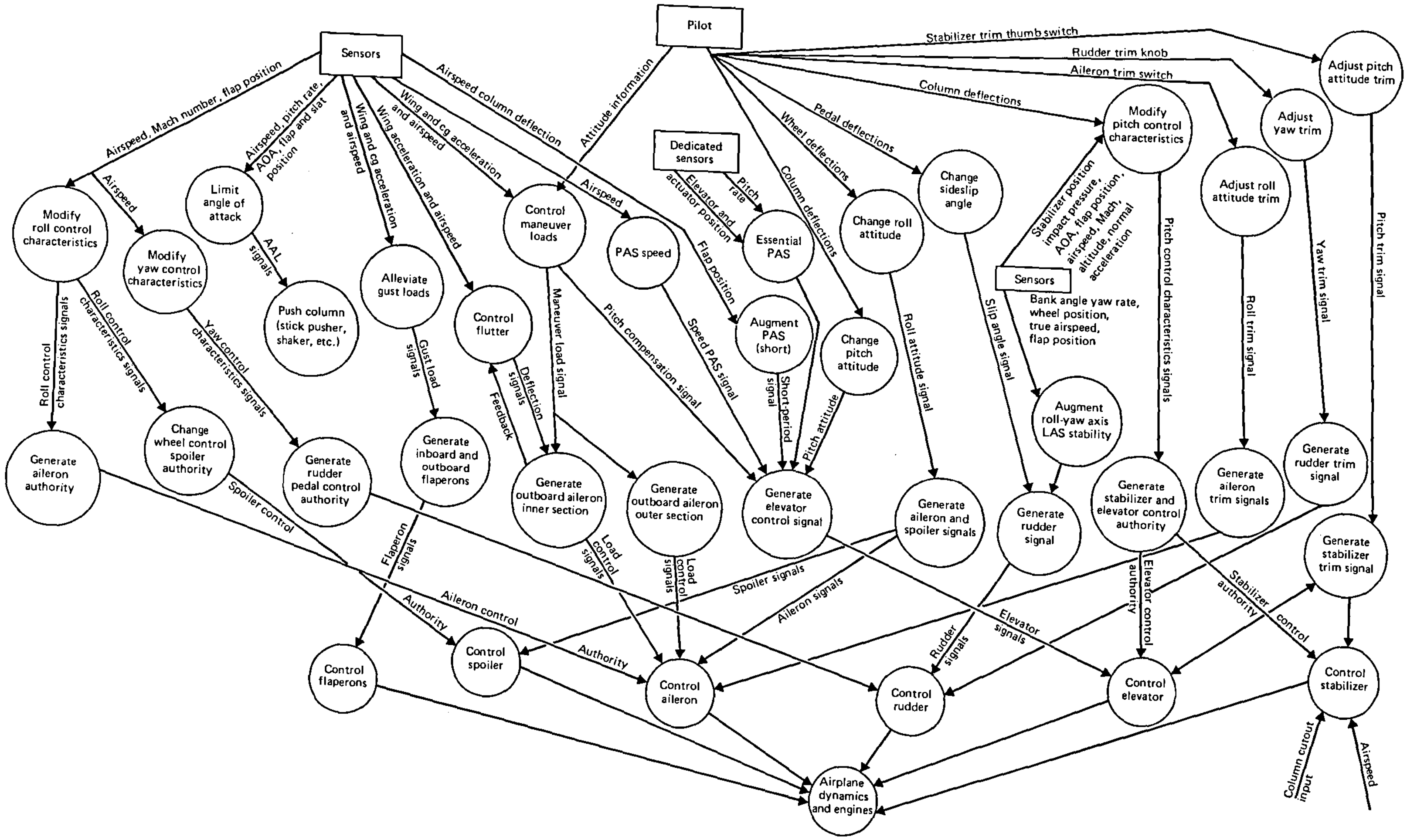


Figure 10. Data Flow Diagram for the Control and Structure Load Relief Group

The ACT airplane exhibits negative stability characteristics over much of the flight envelope, and its longitudinal stability must be augmented by a pitch-augmented stability (PAS) function.

The data flow diagram for the control and stabilize aircraft function (fig. 10) shows the process for PAS along with associated data flows. The Essential PAS function is also shown. The Essential PAS function is mandatory—the minimum acceptable pitch stability signal—and is required for continued safe flight. For this reason, Essential PAS is the basic building block to which all the other elevator signals are combined. The process description for this particular architecture would include details on redundancy, such as quadruple redundancy of a simple fixed-gain, pitch-rate feedback signal, with single signal selection techniques. Section 7.0 gives details of the process description.

The Essential PAS signal is only one of the signals used to generate the elevator control signal that will drive the secondary actuator(s). The control signal is formed by adding the pitch attitude signal, the speed PAS signal, the short-period PAS signal, and the maneuver-load alleviation signal to the Essential PAS signal. This combining process must not degrade the Essential PAS function beyond the postulated function failure probability of 10^{-9}.

It is apparent that a family of suitable architecture designs can be derived from the data flow diagram and that selection of the best architecture will depend on a number of hardware requirements and software decisions. One useful application of the data flow diagram is to identify regions of difficulty as well as pointing to the proposed domains of change. Not only are low probabilities of failure important in the generation of the Essential PAS function, but they are also important in the signal selection, signal combining, and actuator control functions.

In conclusion, the context diagram has provided an overview of the major functions. The individual data flow diagrams for each of these high-level functions illustrate the interrelationships of these data and the processes that make up the function.

7.0 SYSTEM ARCHITECTURE

7.1 INTRODUCTION

Development of Active Controls Technology (ACT) system architecture concepts is strongly influenced by the rapid growth and wide acceptance of digital avionics.

The 1980s mark the beginning of broad commercial transport digital system application and evolution. Introduction of these extensive and complex digital systems may be even more significant for commercial than for military airplanes. Weight savings, improved reliability, design flexibility, and reduced maintenance are just a few of the digital system potential payoffs if the systems are rigorously developed. However, there are some hidden pitfalls along with the potential gains.

The ACT airplane advances the current trend in commercial avionics toward more extensive, more interrelated, and more safety-critical avionic assemblages. Earlier airplanes compartmented design and test of avionic systems into functionally separate areas, with minimal concern for interaction among areas. The present generation of airplanes pushes the limit of complexity for such an approach. The various avionic equipment of any future airplane, such as ACT, must be designed as a single, integrated system, using techniques based on the lessons learned with current commercial airplanes and military and space programs.

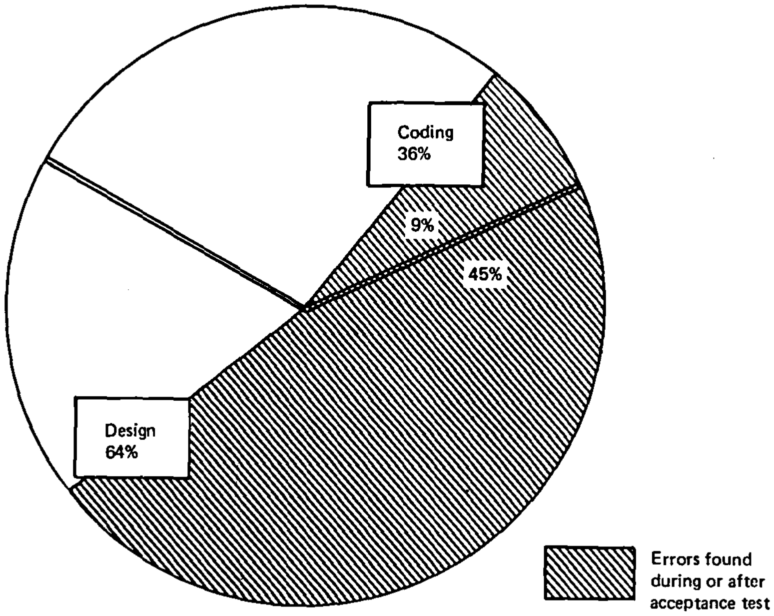
7.2 LESSONS LEARNED

The present complexity of commercial airplanes, with all-digital flight management systems and other related digital systems, is rapidly equaling that of NASA and military space and air vehicles. Yet the commercial airplane manufacturers cannot accommodate the program and budget "elasticities" of military and NASA development and production projects. New airplane product delivery delays are not acceptable to customers, and budget overruns, although eventually paid by subsequent customers, are immediate burdens on the manufacturers. Consequently, budgets, schedules, safety requirements, and standardization requirements are met by maintaining traditional discipline separation, with systems integration becoming a concurrent design task. Thus, units within the avionic suite that must handle real-time integration of many interactive functions of flight tend to require as much luck as acumen in their initial specification of size, throughput, and software volume. And the extensive differences between full field support for these new integrated digital systems and for older systems are just now being fully appreciated.

The implications of digital interface requirements are now becoming apparent to those in the commercial airplane field who are using extensive digital avionics in new designs. Most of the earlier commercial airplane engineering and management experience has been with analog avionics and a few hybrid digital systems. The evolving magnitude of the end-to-end system cost (including costs for maintenance of automatic test equipment and software control) and the potential system interactions are slowly being recognized, along with the ultimate cost inherent in minimizing or deferring such considerations as:

- Verification of system and software design by total system modeling
- Comprehensive review of overall software system requirements
- Software system configuration analysis
- Testable and verifiable software requirements
- Hardware and software end-to-end system interactions
- Hardware and software mode hierarchy, mode regression, and reinitialization
- Software coding to meet precise, verifiable system software requirements
- Software intrasystem and intersystem verification and validation
- "Cradle to grave" hardware and software configuration control by airplane tail number, and engineering analysis and simulation of impact of any software or hardware change prior to recertification

Studies of software-intensive systems development (ref 17) have shown that 54% of the software errors are found during and after acceptance testing, as shown in Figure 11.



Error category	Total	
	Number	Percent
Incomplete or erroneous specification	340	28
Intentional deviation from specification	145	12
Violation of programming standards	118	10
Erroneous data accessing	120	10
Erroneous decision logic or sequencing	139	12
Erroneous arithmetic computations	113	9
Invalid timing	44	4
Improper handling of interrupts	46	4
Wrong constants and data values	41	3
Inaccurate documentation	96	8
Total	1202	100

Source: IEEE (ref 17).

Figure 11. Software Error Sources and Categories

When discovered late in a program, the cost of correcting the errors can be extremely high. In addition, these studies have shown that 28% of the errors found during validation efforts were caused by incomplete or erroneous specifications. Also, this study showed that 12% of the errors were caused by intentional programmer deviations from the specifications. Experience has shown that software development time for the new digital avionic airplanes is substantially longer than initially anticipated. The embedded avionic software in a typical new commercial airplane is over 600 000 words. Considering that over 100 interacting computers can be tied together with many dedicated Aeronautical Radio Incorporated (ARINC) 429 digital unidirectional data buses, this becomes a problem of enormous software complexity.

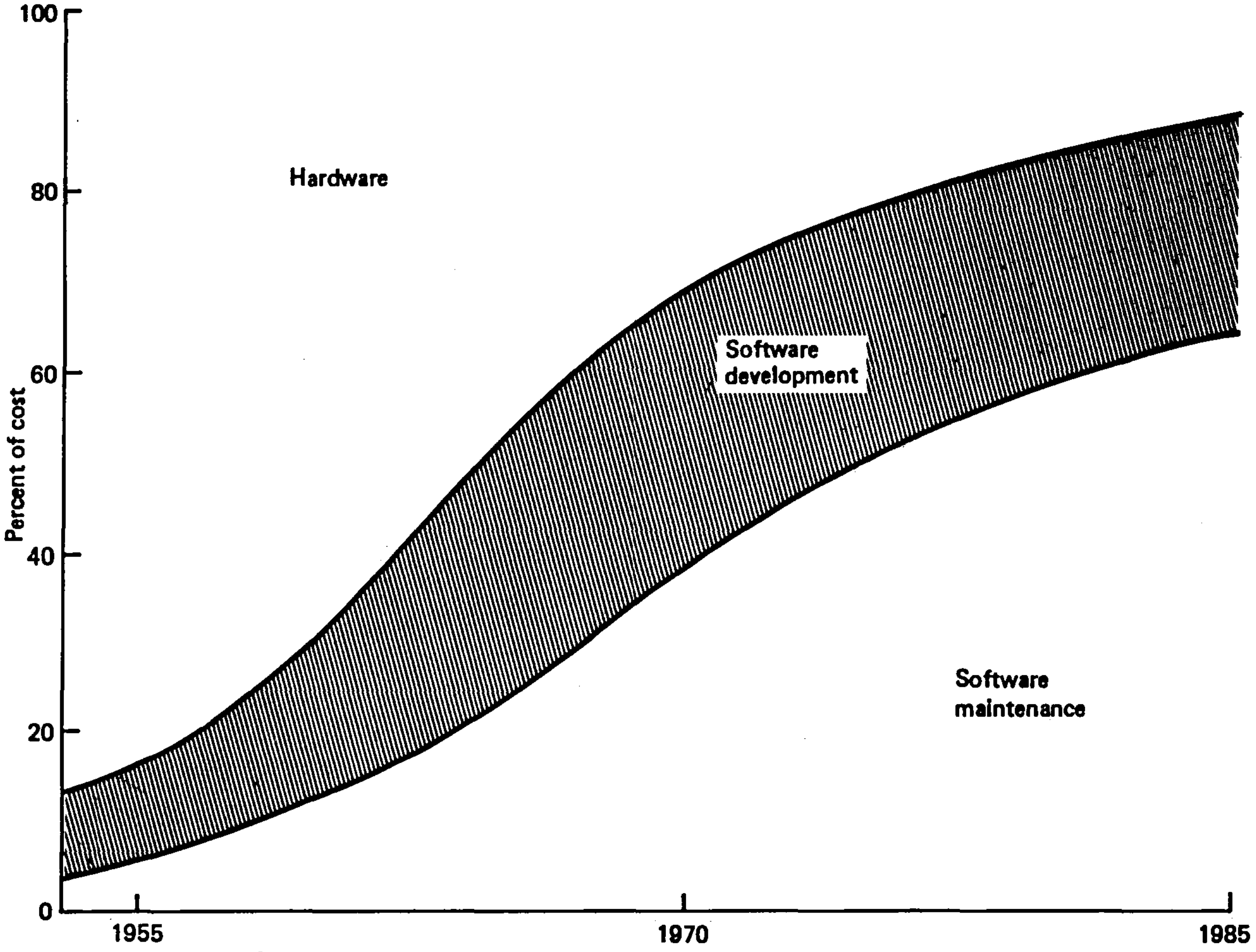
The electronic data processing industry, as well as the military and NASA organizations, has found by long and painful experience that there is no substitute for an early, extensive systems engineering approach to avoid confusion and delays downstream in a large program dependent on complex digital computer systems. If there is an inexpensive or simple solution to this complex problem, it is not apparent at this time. The task now is to develop the least costly way of doing the necessary front-end activity. Knowledgeable organizations are using structured analysis and vigorous systems engineering approaches that tend to cause heavy front loading in a program, with attendant initial time penalties. However, these approaches minimize program slippages during and after acceptance testing and certification and during inservice program phases.

High-technology companies or organizations such as TRW, RCA, APL, and McDonnell Douglas Astronautics are beginning to use sophisticated computer program tools to generate testable, verifiable software system requirements. The software requirements tools must be used before coding software modules to correct the typical endless software recoding of modules, with the attendant patching and debugging that usually occur with open and incomplete specifications. One of these system program aids was prepared under contract with the U.S. Army Ballistic Missile Defense Command by TRW and is called Software Requirements Engineering Methodology. This program has been obtained from TRW by Boeing Aerospace Company and is hosted on a VAX 11/780 computer at Kent, Washington. This program has been used in research evaluations and appears to have a good potential for minimizing the traditional software development errors and resultant indeterminant program delays caused by software problems.

In the past, commercial airplanes have not had the complex interdependency among systems that is now being experienced. The functional complexity and increased performance requirements have resulted from the need for better fuel economy, while at the same time operating in an increasingly complex air traffic system. This will eventually lead to four-dimensional (4-D) airplane performance requirements, with a precise time slot for takeoff to meet a preallocated landing slot and thus allow maximum fuel efficiency and system traffic capacity. Implementation of this concept on an airplane involves flight management systems integrated with essentially all other airplane systems from environmental control systems to electric power distribution. The payoffs in improved safety and fuel conservation warrant careful solution of these interface problems.

The historical approach to certification involves certifying a functional capability with the related line replaceable units (LRU) in the airplane to provide for autopilot, autothrottle, autoland, autobrake, etc. The newer all-digital, complex interactive systems will of necessity cause reexamination of some of the older concepts in partitioning and isolation of functions. For example, a comprehensive flight management computer system in the new-generation airplanes has broad system ramifications, and that system along with the inertial reference system and air data computer system can have far-reaching impacts on the many LRUs in a fully digital avionic airplane. It will be a long—but very important—learning period for both industry and Government to apply the lessons learned in the new families of digital avionic airplanes and to apply the needed disciplines of structured analysis and systems engineering to the next generation of commercial airplanes. The necessary revisions to the basic approach will affect the entire industry and cause extensive changes to the old methods. The old "form, fit, and function" interchangeability criteria must be carefully reexamined, modified, and expanded to satisfy the requirements of a modern digital hardware- and software-configured airplane with complex, interdependent systems and LRUs.

A systems methodology at a top level as applied to an ACT airplane is being developed to enable understanding this new approach and the software system implications therein. Previous experience then has shown that the development cycle for large, complex digital systems is costly, especially in software. In the future, software will be even more of a factor because the ratio of software-to-hardware cost is steadily increasing as shown in Figure 12 (ref 18). Also, there are some key concerns with developing software-intensive



Source: Reference 18.

Figure 12. Distribution of Digital System Costs

systems. As mentioned previously, experience has shown that many software errors are caused by inadequate or poorly understood design requirements and specifications. In many cases, several iterations of "final" software packages are required before acceptable performance is achieved (fig. 13). As systems become more complicated, it becomes increasingly difficult for systems engineers or systems engineering groups to write an adequate initial specification without improved computer-aided systems methodology. If current inadequate system architectural design approaches were continued, private industry would have difficulty supporting the ever-increasing costs and finding the engineering resources to do the job.

Another concern is the decline in productivity with software program size. Figure 14 shows the effort required to develop a program from requirements to verified software. This indicates that the method of partitioning a system from a software point of view has a major impact on the required development effort, cost, and time. Therefore, software considerations should be the major driver in future system partitioning.

The airplane system must be partitioned functionally and physically so that system specifications, coding, installation, and test are simplified and can be further supported with computer design tools. Furthermore, it is mandatory to keep the flight-crucial subsystems small and simple because of their extremely stringent (and expensive) verification and validation requirements.

Recent and projected developments in digital hardware processing capability will make this new system architecture practical. As described in Section 5.0, microprocessor hardware vendors are becoming more conscious of software problems and are helping to solve them by (1) providing major emphasis on software support, (2) designing for higher order language (HOL) implementation even at the silicon-chip level, (3) ensuring software transportability, (4) providing for modular expandability, and (5) building in many self-test and monitor functions in anticipation of user application needs.

Because of the dense packaging, high processing throughput, and relatively low cost of the hardware, microprocessor capability in the future is less critical and can even be underused in many cases. This will permit a single microprocessor type to be used for both simple and complicated functions, thereby reducing the catalog of parts and the number of design and test tools required.

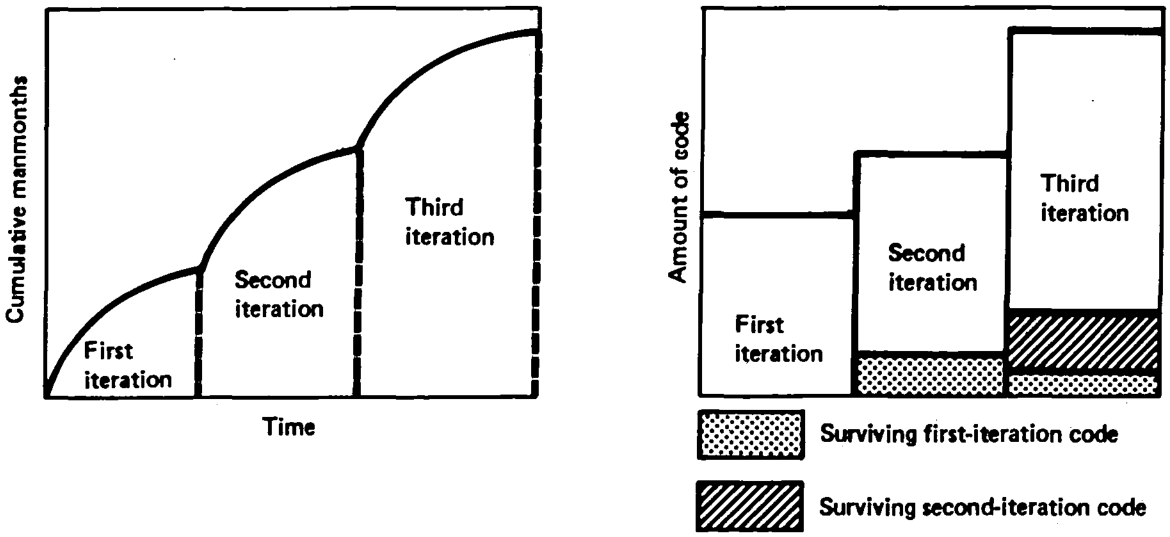


Figure 13. Current Software Design Characteristics

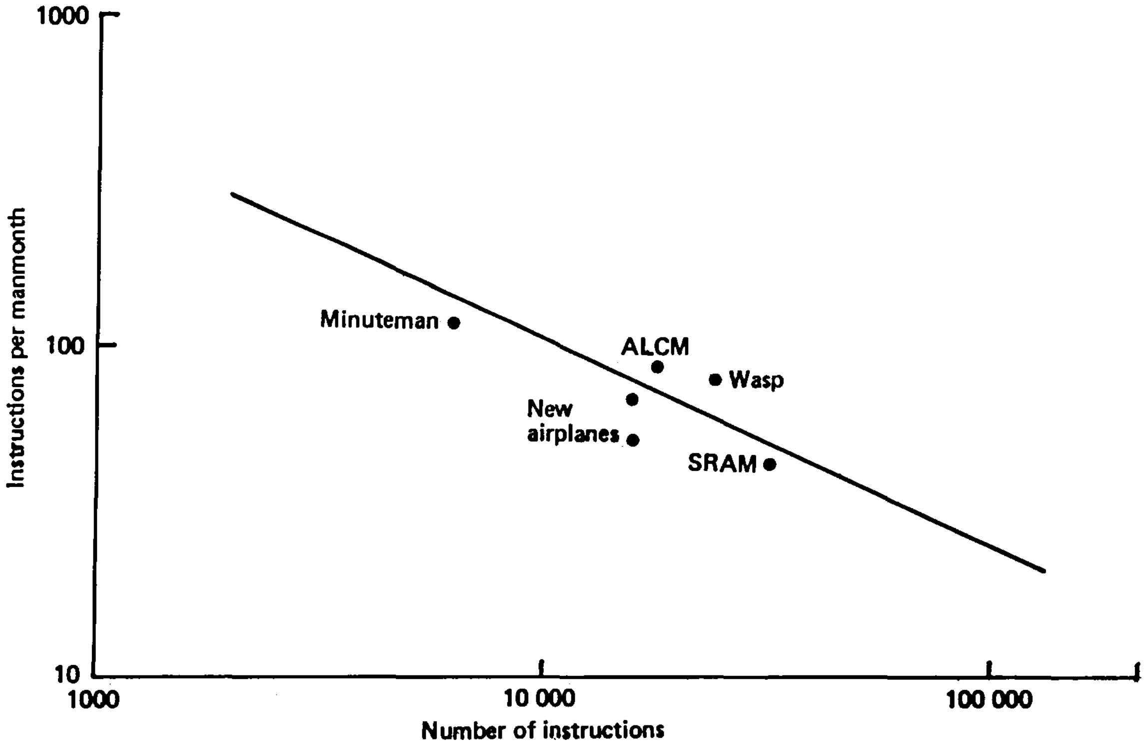


Figure 14. Software Productivity Trend for Program Size

7.3 ASSUMPTIONS AND GROUND RULES

7.4 AUTOFLIGHT FUNCTIONAL MODES

7.5 HIGH-LEVEL PROCESS DESCRIPTIONS

7.3 ASSUMPTIONS AND GROUND RULES

7.3.1 ASSUMPTIONS

As discussed previously, software complexity is the main driver for decentralizing the system functions, both in hardware and software. The subsequent increase in hardware complexity brought about by decentralizing the software is outweighed by design flexibility, ease of reconfigurability, simplified error detection, etc. But because of the large number of digital hardware elements, the digital data transmission system (ARINC 429) used on current commercial transports is probably not practical. The ARINC 429 system, which uses a separate bus for each data source, would impose too high a penalty in hardware complexity, weight, and installation cost. Many potential benefits of hardware modularization and software decentralization would be lost because of the inflexibility of intersystem and intrasystem wiring that is difficult to service, modify, or expand once installed on a large airplane. Thus, multiple-access, two-way digital data buses with autonomous terminals are assumed to provide the system data links. This data link differs from the MIL-STD-1553 link in one major respect: no bus controller is required because of the terminal's autonomy. A fault in the MIL-STD-1553A bus controller can result in failure of all terminals on the bus. A fault in a given MIL-STD-1553B bus controller requires additional complexity and overhead burden to permit reliable detection of a faulty bus controller and to provide successful bus controller transfer to one of the remaining good bus controllers. The autonomous data bus and terminal standard configuration envisioned in this study—and fundamental to the system architecture—has the potential for an active transmitter fault causing interference with other terminals on the bus. Because of this, these standard autonomous data bus terminals incorporate an independent monitor element to disable the transmitter if it violates protocol. Therefore, a central bus failure occurs only with a dual failure in a transmitter and its monitor or with a bus medium failure. Therefore, autonomous terminal failures will normally result in a shutoff of the elements the terminal services but will not affect other terminals on the bus.

Analysis of total system performance, including effects of data rates, frame rates, transport delay, data freshness, and multiple digital sampling, is beyond the scope of the current task and is deferred to a later design phase.

The decision to base system architecture on the Initial ACT Airplane configuration and upon the ACT Selected System configuration is another constraint. The 1990s ACT Airplane configuration and functions will no doubt differ from the Initial ACT Configuration. But the Initial ACT Configuration is representative of the ACT functions and criticality that would likely be in a 1990s ACT airplane. It is expected that the system architecture will evolve as the ACT airplane definition progresses, but changes to the ACT airplane configuration will not be the principal factor affecting system architecture decisions. The most important factors affecting those decisions will be unanticipated technology advances and performance, reliability, or maintainability deficiencies found by more detailed analyses and tests than have been possible during this high-level system study. A significant advantage to the top-down systems engineering approach applied to this study is that system deficiencies should not affect any level higher than the level in which they were found.

Subsection 7.3 contains assumptions and ground rules for the system architecture study. Because of the limited scope of this study phase, some of the rules were not explicitly required but are presented for completeness in anticipation of further detailed study efforts.

7.3.2 GROUND RULES

The following ground rules are imposed as constraints on the architectural structuring of the integrated ACT/Control/Guidance System.

7.3.2.1 General

- The airplane configuration will be the Initial ACT Configuration, as defined in References 4 and 5.
- All LRUs interchanging data via the autonomous, multiple-access, two-way digital data buses will use the same type of standard bus interface.
- Loss of receiver function at any bus interface will not affect the other data link functions on the bus.

- For crew systems planning, the airplane will have a two-person cockpit.

- The ACT system configuration, used for integration with other avionic functions, will be based on the ACT Selected System (refs 6 and 7), except for the addition of fly by wire and deletion of flutter-mode control for a 1990s airplane.

- Integrated ACT and avionic system configurations will be based on the supposition that the all-electric airplane will be practicable by the 1990s.

- The Essential PAS function will be kept separate from integration of the other ACT/control/guidance functions.

- Flight crucial functions must not be affected by failure of lower criticality functions. System functions will be grouped by safety criticality.

- System design should preclude single-point failures (loss of function due to failure of a single system element).

7.3.2.2 Sensors

- Shared sensors will be used to the maximum extent practicable as constrained by a desire to isolate functions of differing criticalities.

- Sensor redundancies will be driven by the most critical downstream functions.

7.3.2.3 Processors

- Processing functions will be LRU separated, based on path or function criticality. This means that decentralized processing will be extensive, and multifunction processing in any single unit will be an exception to the design rule.

- Very few types of processing hardware units will be used, and they will be chosen to best satisfy the various processor applications (e.g., large number-crunching requirements, bit-processing requirements).

- With decentralized processing and few processor types, common software functions will be used extensively (allowing use of HOL library for configuration control and using a large-scale software development system for algorithm development and checkout and for compiling machine instructions).

- System design will be based on the use of autonomous processing, to the maximum possible extent, together with careful consideration of the difficulties inherent in solving the data timing problems for interdependent, distributed function processing.

7.3.2.4 Actuators

- Surface actuators will be shared among ACT and flight control functions to the maximum possible extent. This method of system implementation must ensure that actuation of functions of lesser criticality does not affect functions of greater criticality.

- It will be assumed that electromechanical actuators (EMA) and integrated electric motor hydraulic pump actuation packages of the requisite load and response capacities will be used in the 1990s ACT Airplane.

7.3.2.5 Data Links

- Multitransmitter, bidirectional, broadcast-mode serial data buses will be the standard for data interchange between LRUs.

- Data links delivering data for system functions of greater criticality must be relatively "immune" from faults caused by system functions of lesser criticality.

7.4 AUTOFLIGHT FUNCTIONAL MODES

Structured analysis techniques were used to develop the candidate functional architecture, a context diagram of which is shown in Section 6.0 (fig. 6). A simplified variation of that diagram, shown as Figure 15, illustrates how the various processes are interconnected to perform four typical operational modes. Figures 16 through 19 show data flow paths for the manual mode, manual guidance with automatic control mode, automatic guidance with manual control, and automatic guidance with automatic control, respectively. The heavier lines show the major functional mode paths in each figure.

The illustrated operating mode data flow diagrams do not delineate system physical architecture choices. The primary function of the diagrams is to ensure understanding the operating modes and to show that the modes do not differ from the data flows and processes of current-generation commercial transports at this high level.

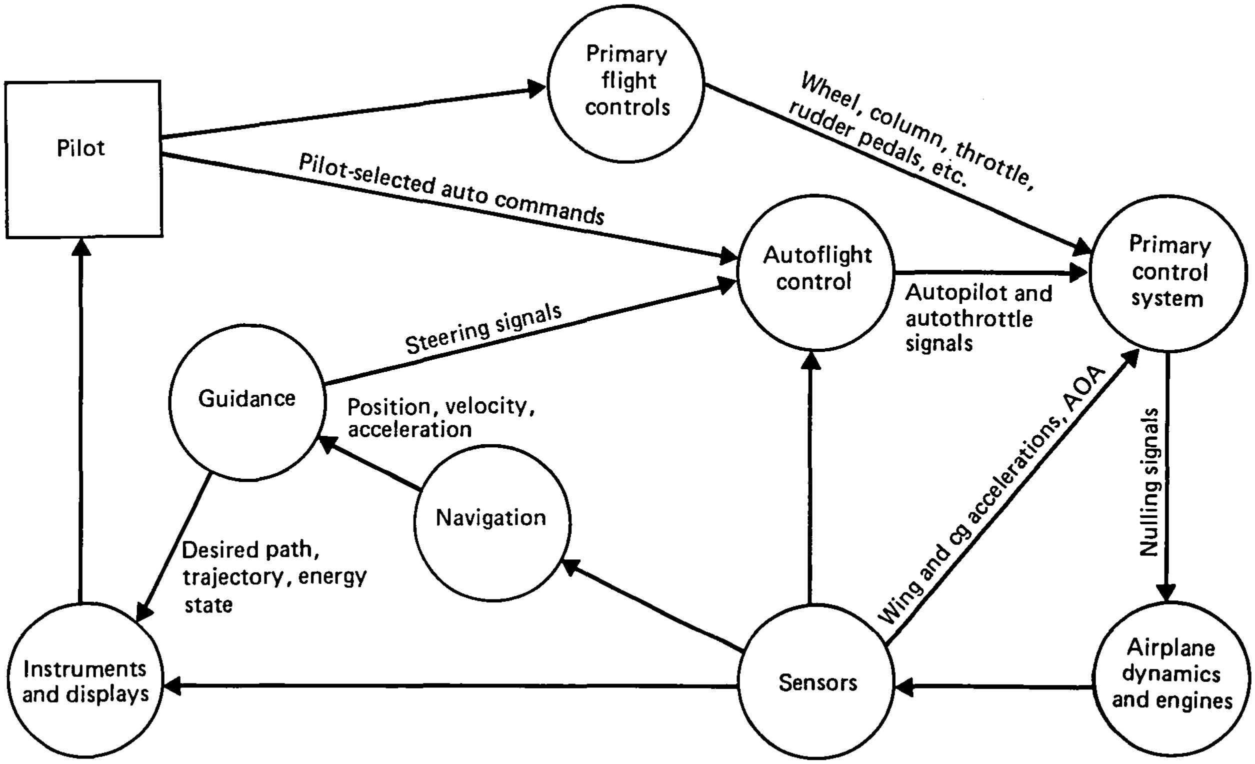


Figure 15. Simplified Context Diagram

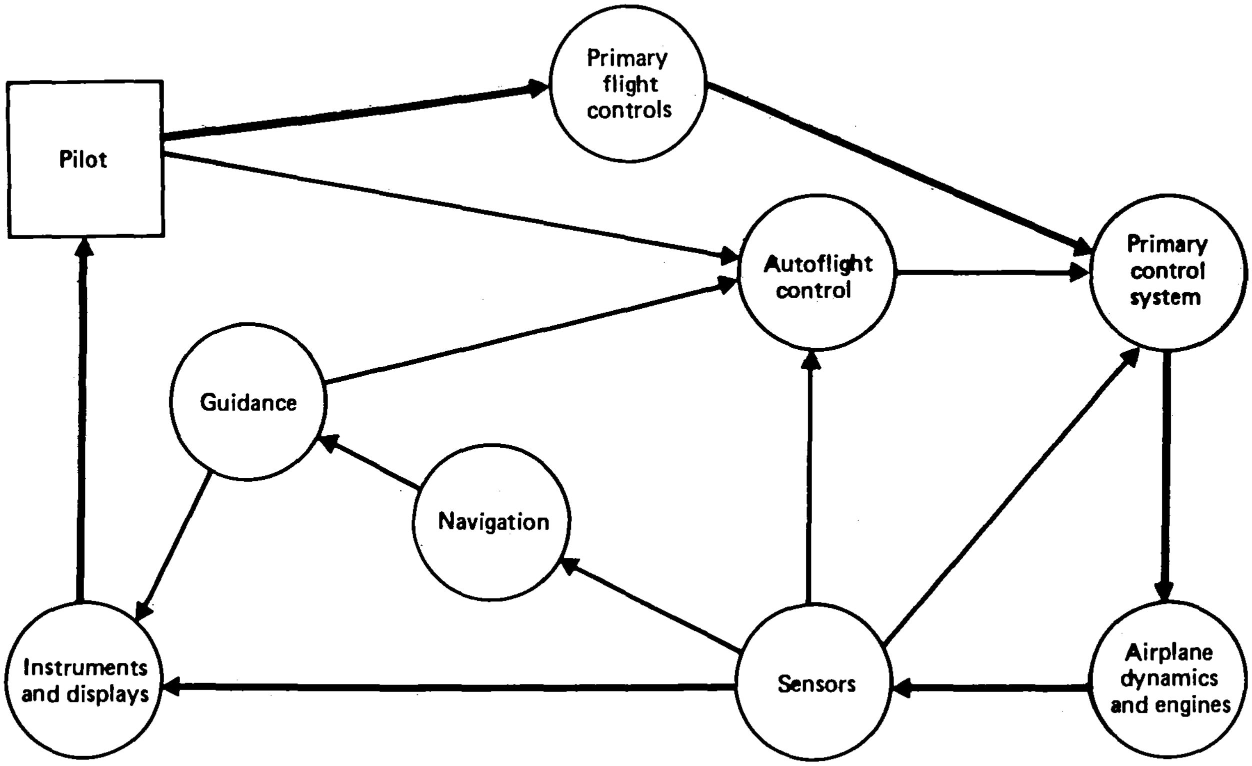


Figure 16. Manual Mode

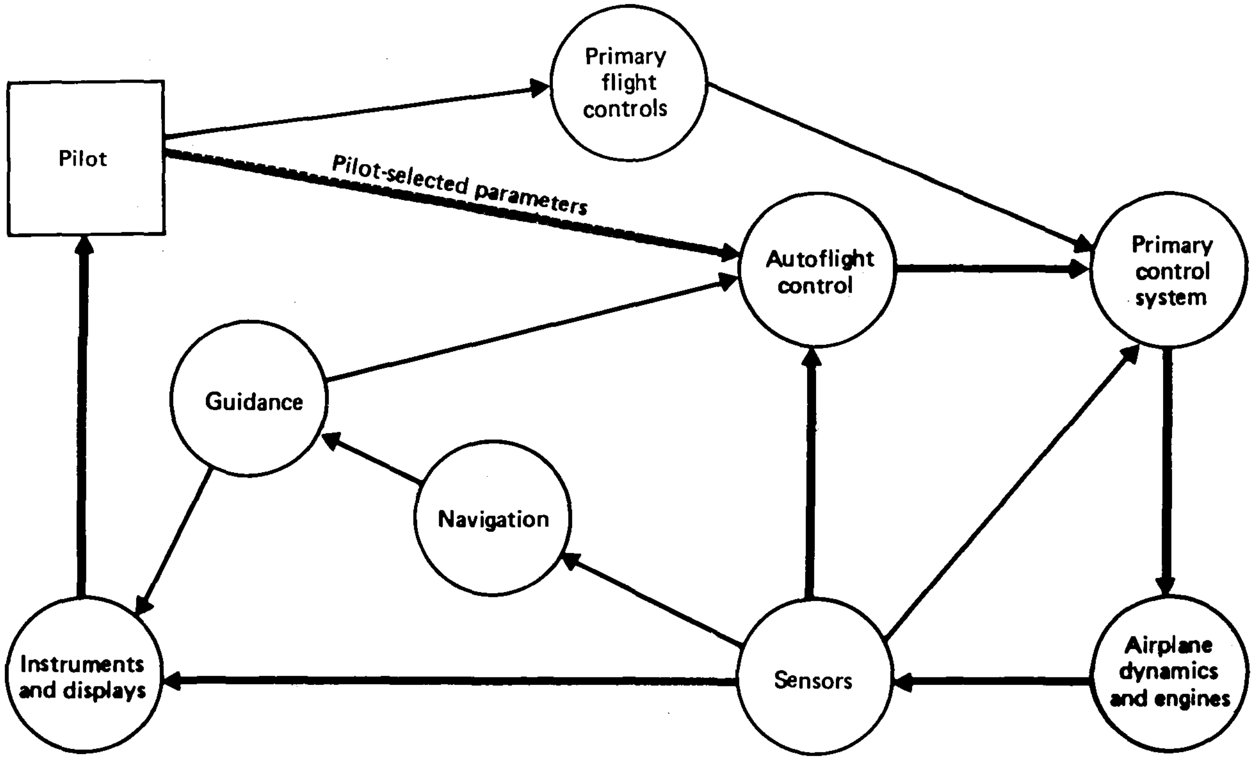


Figure 17. Manual Guidance With Automatic Control

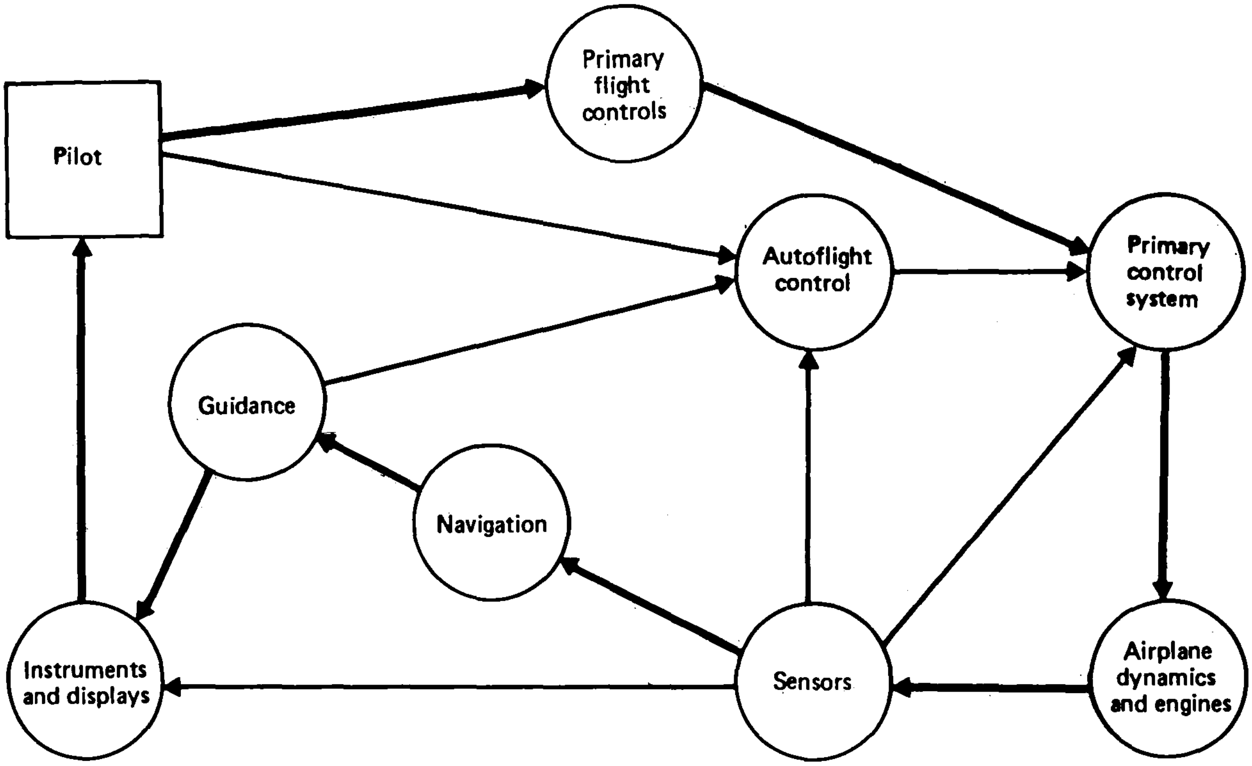


Figure 18. Automatic Guidance With Manual Control

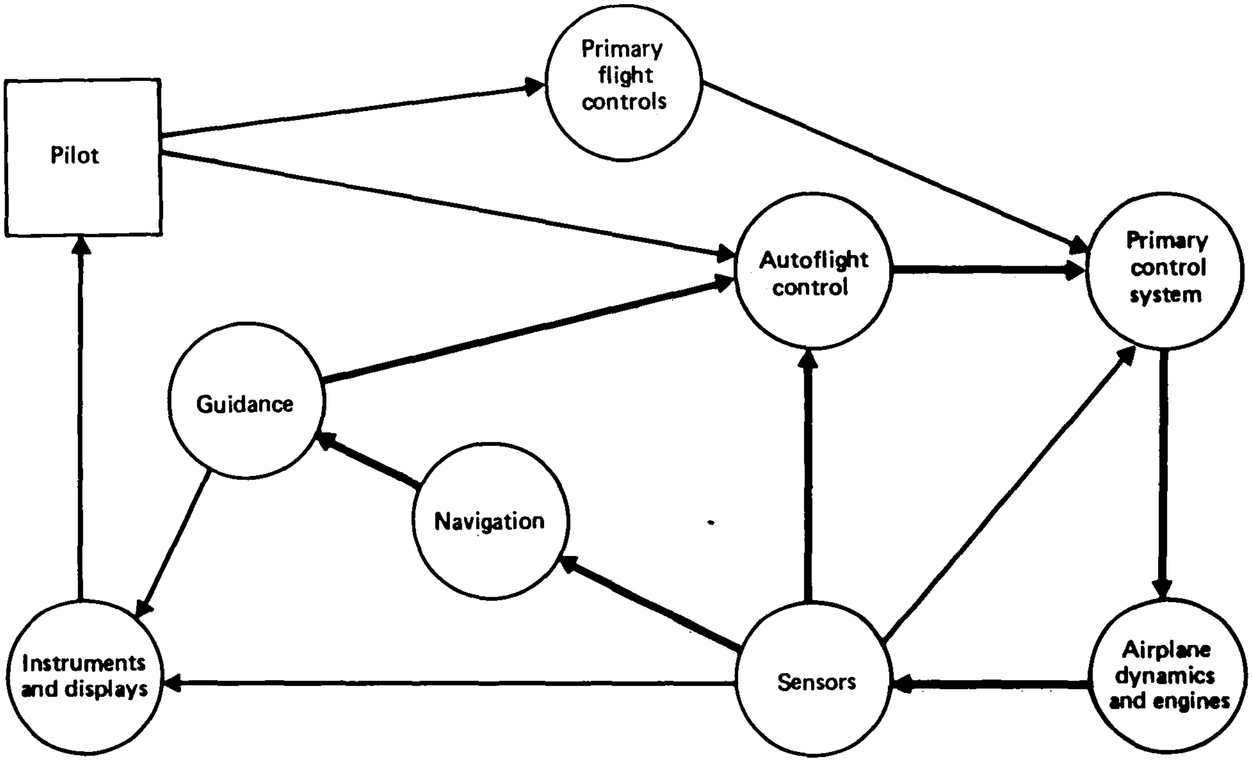


Figure 19. Automatic Guidance With Automatic Control

7.5 HIGH-LEVEL PROCESS DESCRIPTIONS

Figure 15 presents a simplified context diagram of the high-level functional processes and data flows required for airplane operation. The following subsections define the principal functional elements embedded in those processes. The system physical architecture decisions are still not affected by these intraprocess descriptions; the main purpose of the descriptions is to provide familiarity with the high-level processes.

7.5.1 PRIMARY FLIGHT CONTROL PROCESSES

Primary flight control processes are those processes normally associated with action by the pilot, such as inputs through appropriate movement of wheel, column, throttles, rudder pedals, trim, etc.

For descriptive purposes, this subsection refers to the pilot's pitch axis command as a column deflection, while the pilot's roll axis command is termed a wheel deflection. This convention is taken to ease the descriptive task and is not meant to define the type of pilot input device or the type of input transducer (force or position).

7.5.2 NAVIGATION, GUIDANCE, AND AUTOFLIGHT CONTROL PROCESSES

At this functional level, it is appropriate to group the navigation, guidance, and autoflight processes into one generalized process because of their close interrelationship and for ease of understanding. When the processes are separated later, it will be found that similar functions might be performed in more than one process group; however, this is consistent with the assumptions and ground rules in Subsection 7.3.

The navigation, guidance, and autoflight processes are composed of the following functions:

Flight Management—Within the flight management functions, pilot-entered flight routes are defined and flight profiles are optimized and predicted. Automatic navigation is performed based on pilot entry and sensor data. Navigation and performance data are also available for display.

Flight Guidance—The flight guidance function provides thrust control and thrust limit determination. Guidance commands to acquire and track flightpath parameters (pilot selected and flight plan derived) are determined.

Autoland Guidance—The autoland guidance function provides attitude control and landing path guidance through touchdown and rollout.

7.5.3 PRIMARY CONTROL SYSTEM PROCESSES

The primary control system accepts inputs from the primary flight controls (pilot) or the automatic flight control process functions to perform the following functions:

Thrust Axis Control—Control of the throttles is directed from the primary flight controls or the automatic flight controls through the autothrottle actuators, but speedbrake control is accomplished through the primary control system by spoiler control.

Airplane Configuration Changes as a Function of Flight Phase—The leading-edge slats, trailing-edge flaps, and landing gear comprise the equipment that configures the airplane for takeoff, cruise, and landing.

Structural Load Relief—Relief of maneuver and gust loads is achieved by symmetric aileron deflections. The gust loads are also alleviated by flaperon movements.

Airplane Attitude Control and Stabilization—Basic pitch, roll, and yaw controls are accomplished by elevator, aileron plus spoiler, and rudder variations, respectively. Modification of pitch, roll, and yaw characteristics changes the effective feel of primary pilot flight controls. Short-period and speed mode pitch-augmented stability is done by computing the appropriate control laws and providing signals for elevator control. Roll-yaw stability augmentation requirements are met by rudder control.

7.5.4 AIRPLANE DYNAMICS AND ENGINE PROCESSES

These processes include response of the airframe to control system deflections, response of the engine to throttle movement, and interaction of the airplane with the environment. Response and interaction are sensed by the sensor processes, and this information is used to complete the control loop back to the pilot or to the other system processes.

7.5.5 SENSOR PROCESSES

Sensor processes include measuring or detecting wing and body motion, air data parameters, airplane control surface position, altitude, attitude and direction, instrument and microwave landing system signals, very-high-frequency omnidirectional range (VOR) and distance measuring equipment (DME) signals, engine performance variables, etc.

7.5.6 INSTRUMENT AND DISPLAY PROCESSES

The following indicators of flight conditions or system status are displayed: airspeed and Mach number, altitude, vertical speed, attitude (pitch and roll), engine thrust, direction (heading and track) turn rate, and time.

Subsystem performance indicators (e.g., engine, hydraulics, and electrical) are also displayed. Navigation and guidance display functions are bearing and/or distance to navigation aids, bearing and distance to severe weather, deviation from selected landing system path, autoflight pitch, roll, airspeed, thrust commands, selected thrust limits, desired flight profile, airplane state (position and velocity), aeronautical chart data, and performance handbook data.

The flight condition visual or aural alerts are overspeed, improper configuration, fire warning, autopilot disconnect, ground proximity, and ACT system faults.

Abnormal status alerts are generated for the following systems: air-conditioning, autoflight control, electric power, fire protection, flight control, fuel, hydraulic power, ice and rain protection, instruments, landing gear, navigation, pneumatics, auxiliary power unit, doors, engine control, anti-ice, engine indication, oil, etc.

Appendix C contains a more detailed tabulation of instruments and displays.

7.6 PRELIMINARY ARCHITECTURE

7.6 PRELIMINARY ARCHITECTURE

Figure 20 is the high-level data flow diagram for the preliminary architecture. Only slight differences exist between this figure and the context diagram (fig. 15). These differences result from expansion of the primary control system process into its flight augmentation and flight essential components. The sensor process of Figure 15 now appears as sensors and processors. The navigation, guidance, and autoflight control processes are all included within the new navigation, guidance, autoflight control, and attitude management grouping in Figure 20.

The bus structure for the preliminary architecture shown in Figure 20 is composed of four digital bus structures (A), (B), (C), and (D) and a dedicated (E) analog configuration. The sensor bus (A) contains data that are time critical and necessary for critical system functions. The data handled by the management bus (B) are non-time-critical data that provide control information and system configuration. The systems bus (C) contains time-critical data that are also provided at a constant update rate to perform mission-oriented and autoflight functions. The constant update rate actuator bus (D) provides the necessary data to command and feedback control the surface controllers and tactile attitude warning device (stick shaker). The analog, hardwired interconnections (E) handle the flight essential functions. Table 11 shows the preliminary architecture elements that make up the processes shown in Figure 20. These elements will be used in the following discussions. Subsection 7.6.2 describes the functions allocated to the elements.

Descriptions of the five processor groups in Subsection 7.6.2 are purposely generalized. A definite candidate for these groups would be a micromainframe central processing unit (CPU), such as the Intel 432, that handles general data processing and a parallel array of input/output (I/O) processors to handle time-critical functions. Final selection of processor group architecture will require a detailed performance study of advanced digital hardware, and this information is only now beginning to appear in literature.

7.6.1 OVERVIEW OF PRELIMINARY ARCHITECTURE

This section describes allocation of system functions to elements and general interconnection of these elements in the preliminary architecture. In general, the architecture integrates the system functions by data buses, while separating those functions into smaller processing units. The concept is characterized by sharing sensors,

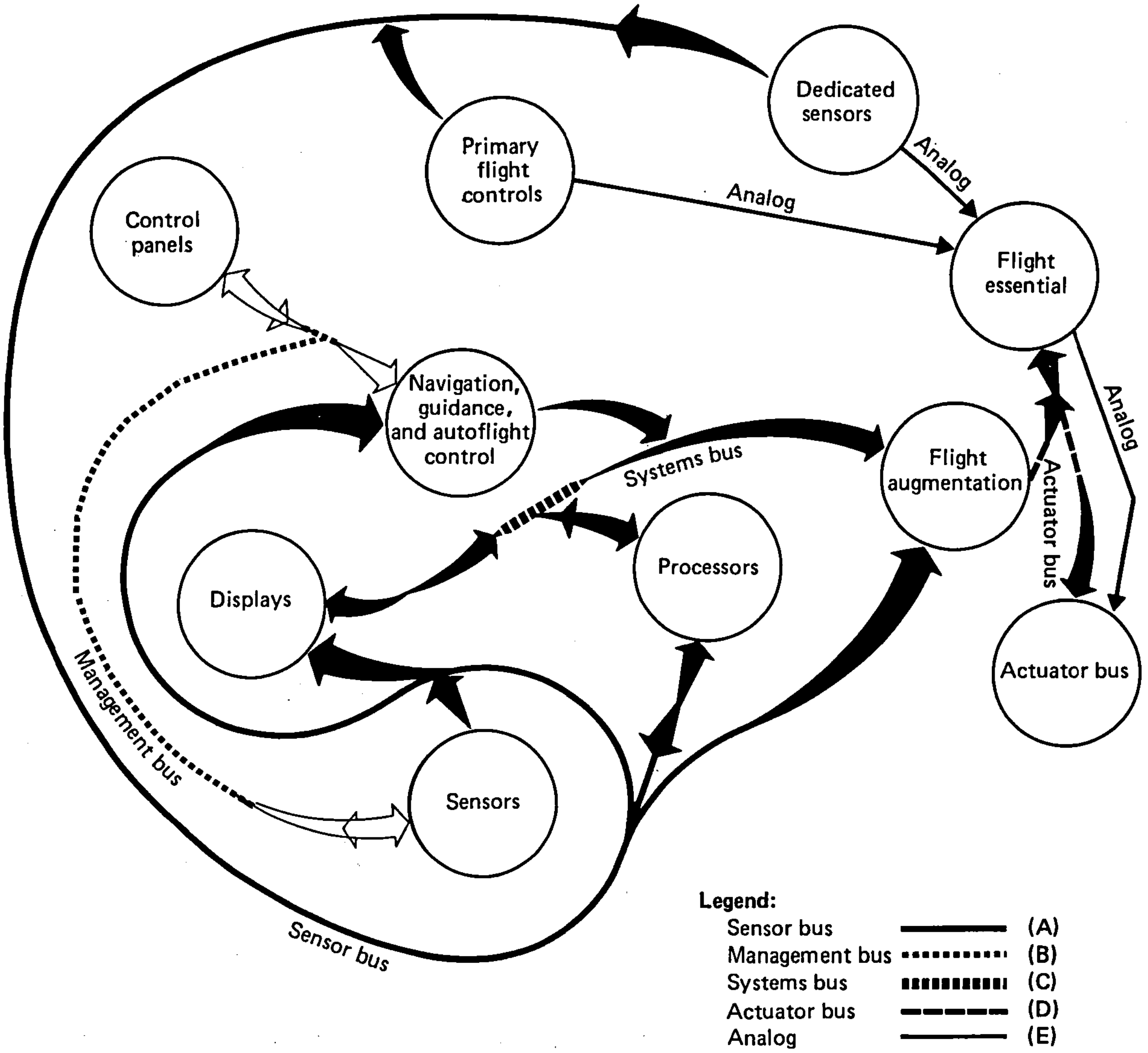


Figure 20. Bus Structure Data Flow

Table 11. Definition of Architecture Elements

Architecture element	Abbreviation
• Control panels	
• Autoflight control panel	ACP
• Communication and navigation status panel	CNSP
• Multifunction panel	MFP
• Navigation, guidance, autoflight control, and attitude management	
• Autoland processor group	ALPG
• Flight guidance processor group	FGPG
• Flight management processor group	FMPG
• Display	
• Head-up display	HUD
• Attitude director display	ADD
• Flight instrument display	FID
• Horizontal situation display	HSD
• Engine display	ED
• System display	SD
• Sensors	
• Wing motion sensors	WMS
• Body motion sensors	BMS
• Air data sensors	ADS
• Surface position sensors	SPS
• Radio altimeter	RALT
• Instrument landing system	ILS
• Microwave landing system	MLS
• Pneumatic system	PS
• Engine sensors	ES
• Fuel sensors	FS
• Very-high-frequency omnidirectional range and distance measuring equipment	VOR/ DME
• Transponder	XPOND
• Processors	
• Air data processor	ADP
• Attitude processor	AP
• Flight augmentation processor group	FAPG
• Actuators	
• Autothrottle actuator	A/T ACT
• Outboard aileron	OB AIL
• Inboard aileron	IB AIL
• Rudder	RUDD
• Elevator	ELEV
• Flaperon	FLP
• Spoiler	SPOIL
• Stabilizer	STAB
• Stick shaker	STICK
• Flight essential	
• Flight essential processor group	FEPG
• Dedicated sensors	
• Dedicated pitch gyros	DPG
• Primary flight controls	
• Pilot flight controls	PFC

by decentralization of top-level functional processing among several computing elements, and by separation of functions by criticality. The result is an overall simplification of the system software by accepting greater hardware complexity.

The groupings and interconnection aspects are preliminary at this time. Grouping is driven by criticality considerations and results in several system functions being accomplished through the joint effort of several elements. Although these function-split concepts appear to be theoretically feasible, more work will be required to specify the algorithms by element and the data transfer and timing aspects to the level required for concept verification.

Figure 21 presents an overview of the preliminary system architecture. As described previously, the system is integrated by digital data buses; there are four different types in the preliminary architecture. The major sensor, management, and systems data bus interconnections are shown respectively in Figures 22, 23, and 24. These figures also show which elements receive data from the bus and which elements transmit data on the bus.

Some general comments should be made about the architecture, which is based on the ACT Selected System for the Initial ACT Airplane with the addition of fly-by-wire functions and deletion of flutter-mode controls. All the primary control surfaces (elevators, ailerons, and rudders) are signaled through force voting secondary actuators. Two sets of secondary actuators in series generate a mechanical input signal to the power control actuator that moves the surface. One set of secondary actuators is dedicated to the basic control functions and the crucial pitch stability function (elevators). The remaining set of secondary actuators is dedicated to the other active control, augmentation, and automatic flight functions. The basic control secondary actuators are signaled over analog, hardwired links, while the other secondary actuators are signaled over digital data bus links. Secondary control devices (flaperons, stabilizer, spoilers, and stick shaker) are commanded on digital data bus links and do not use intermediate secondary actuators. The architecture is very sensitive to this assumed configuration.

The sensors used by the crucial system functions, pitch gyros, and pilot control input sensors are also connected to the rest of the system through the sensor bus. Pitch gyro information can be used in the failure isolation process for the body motion sensor elements. Pilot control information is used by the augmentation and autoflight system functions. This interconnection must not affect the crucial functions.

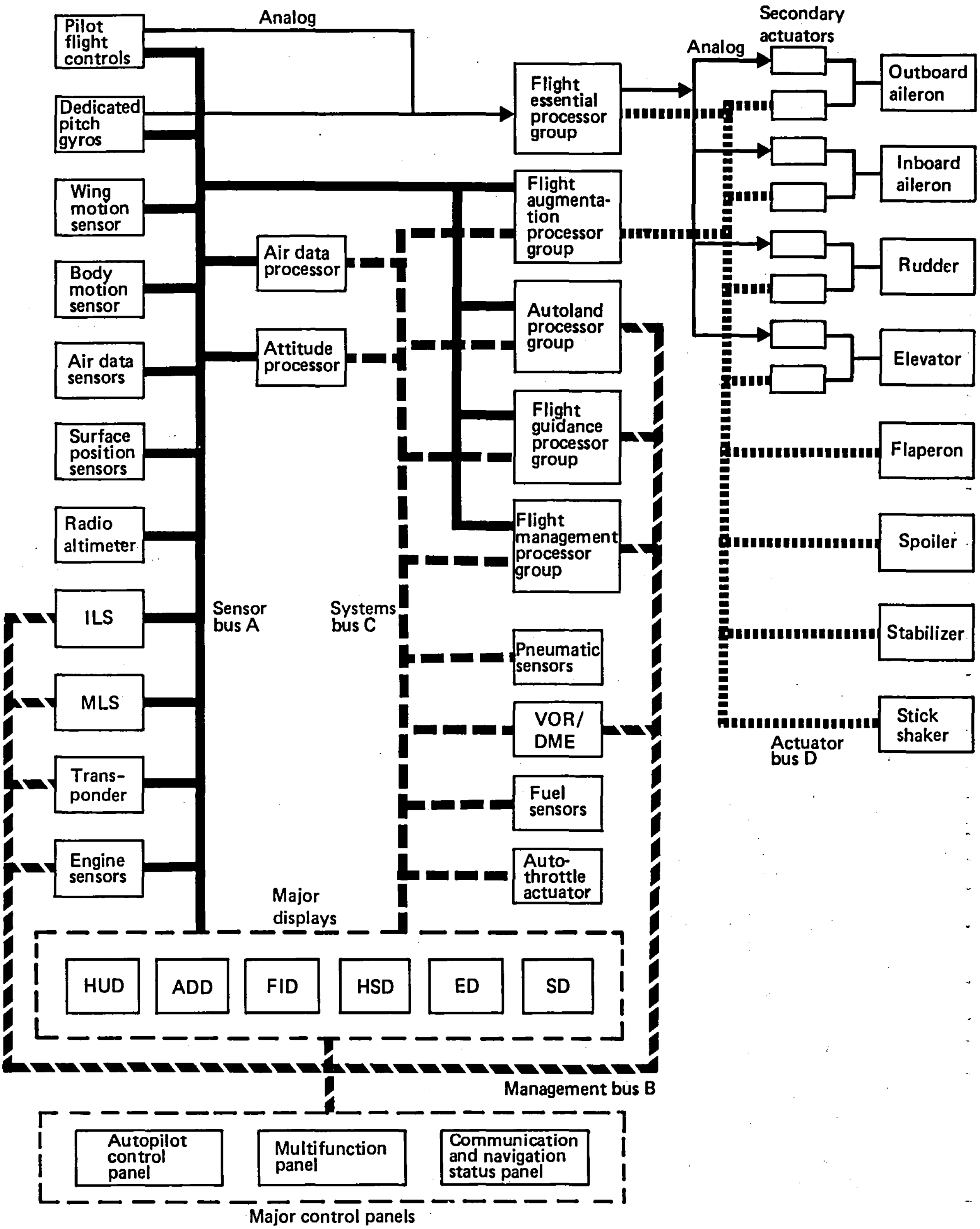


Figure 21. Preliminary Architecture Overview

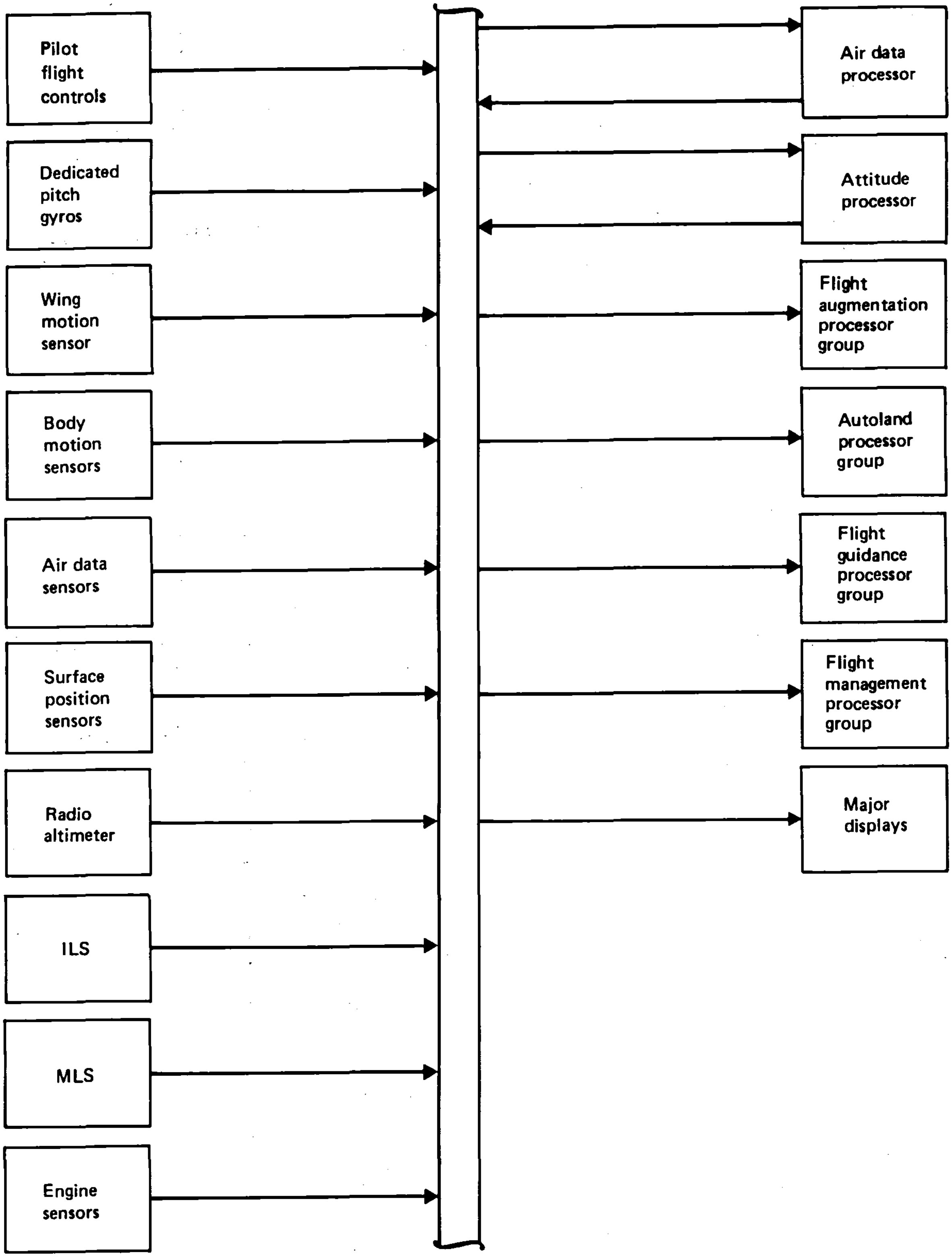


Figure 22. Sensor Bus Interconnections

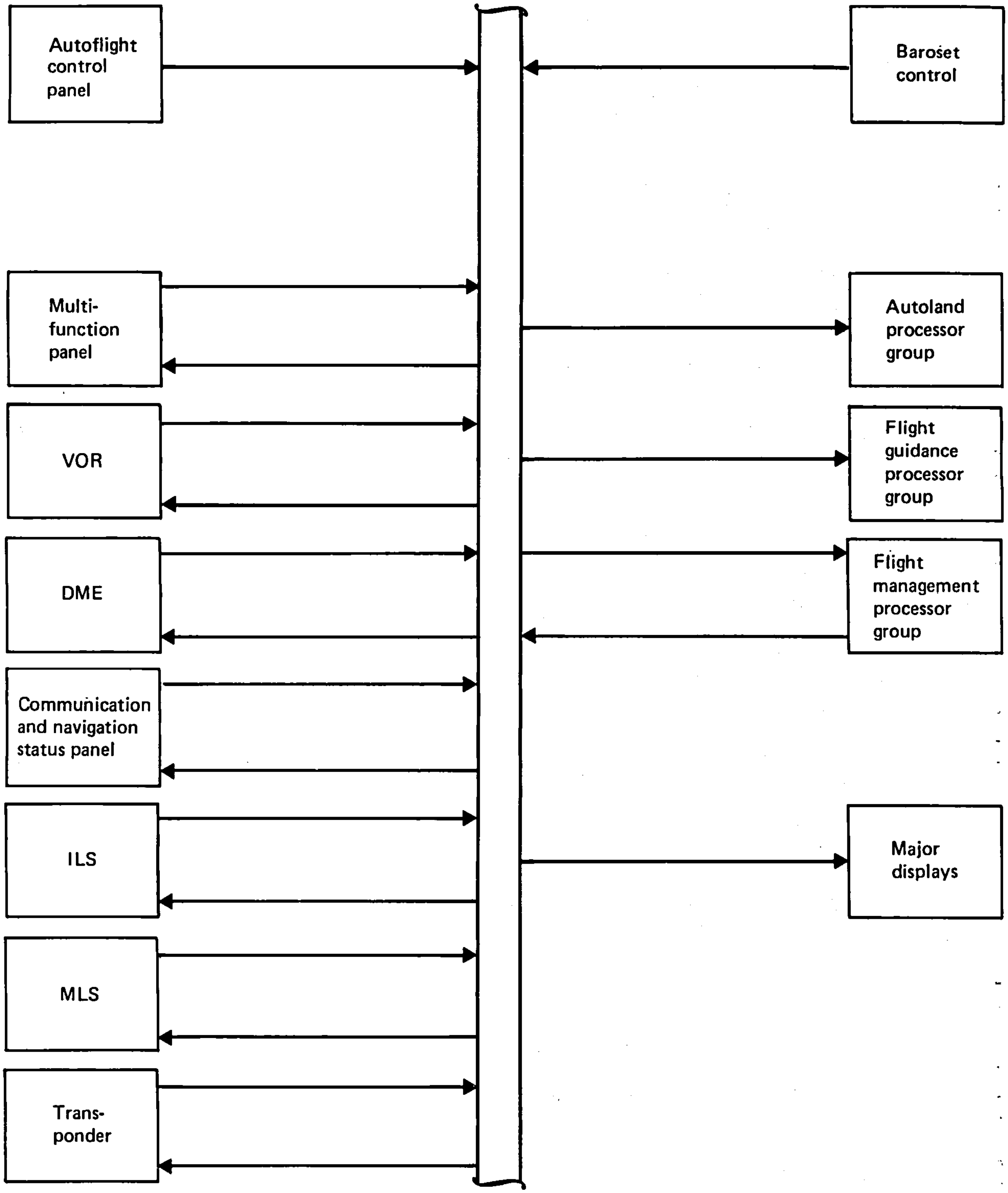


Figure 23. Management Bus Interconnections

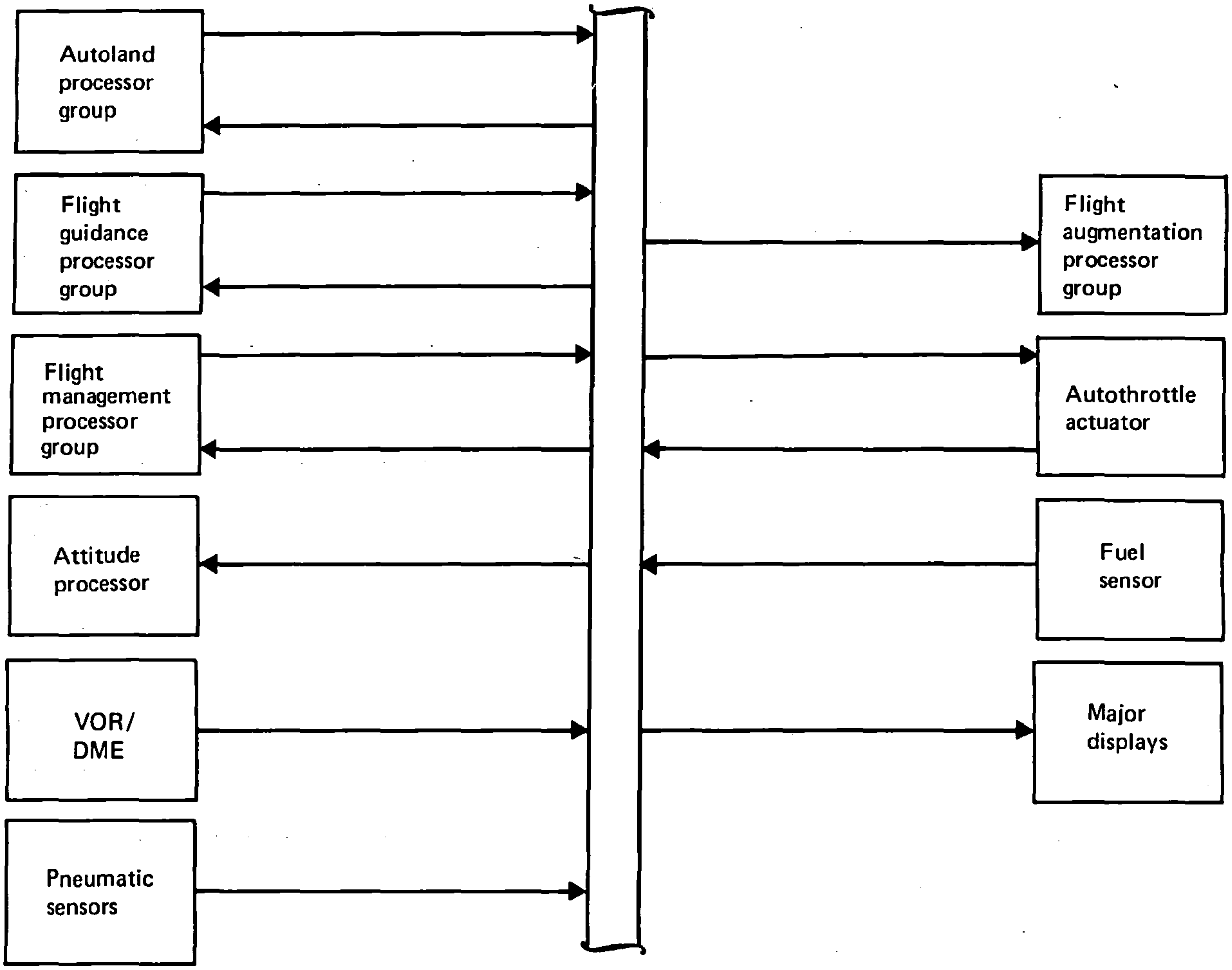


Figure 24. Systems Bus Interconnections

The air data system includes a sensor group that puts raw measured data onto the sensor bus and a processor group to provide calibrated, computed air data. With this separation, the more critical functions can use the "raw" information directly or use it in a degraded operational mode if the air data computation function is lost.

Similarly, the functions normally performed in a current ARINC 700 inertial reference system (IRS) have been separated into more than one element in the preliminary architecture. The basic inertial measurement functions have been allocated to the body motion sensors, which put data directly on the sensor bus. The more critical system functions can use these data directly. Attitude and orientation functions of the IRS are allocated to an attitude processor. Thus the source of more critical system data is separated from the source of less critical navigation data. This split is conceptually possible but will require some intermediate data transfer between the resulting separate elements. Details of the algorithms by element and the intermediate data transfer requirements must be developed in future study efforts.

Because of the assumed configuration of the actuation system and manual flight control elements, the autoflight surface commands must be routed through the flight augmentation processor group (FAPG). The functions of the autoflight system are workload relief and economic enhancement. The principal exception to this is the Category III autoland capability. It is commonly assumed that loss of automatic attitude control from just prior to touchdown through the first portion of landing rollout in actual Category III conditions is catastrophic. Therefore, this portion of the autoflight system—the functions of vertical and horizontal landing path tracking, vertical path flare, and rollout lateral path guidance—has a much higher criticality than the other autoflight functions. If the principle is followed that functions should be separated by criticality, then these more critical functions should be separated from the other functions in the autoflight system. This is done with the autoland processor group. This group generates all control surface commands for the autoflight system and also provides guidance to track the landing path signals. Keeping these functions separate allows redundancy to be specified separately but makes the design more complex from a hardware standpoint. The rest of the autoflight system is based on the assumption that the guidance and control functions can be separated into distinct processors dedicated to specific outer guidance loops, each based on different time-scale dynamics. Again, the algorithms by element and required intermediate data transfer must be fully defined in later studies. In summary, the architecture is preliminary and there are many areas where obvious improvements can be made. In addition, from a performance standpoint, feasibility work needs to be done to realize the benefits of partitioning.

7.6.2 PRELIMINARY ARCHITECTURE FUNCTIONAL GROUPING

This section presents an overview of the functions performed in each of the architecture elements. These descriptions are brief and are intended to allow understanding of the partitioning. Each element is listed followed by the description of the key functions performed. Descriptions of several elements are limited to those functions that take part in the high-level functions being addressed for the ACT/Control/Guidance System. Other supplementary functions that will certainly be part of the integrated avionic system are not discussed or shown.

7.6.2.1 Flight Essential Processor Group

This group contains the flight essential processor and flight essential controller and performs the following:

Basic Pitch Control—Basic pitch control deflects elevators proportional to pilot's control column deflection. In degraded operation, the proportionality ratio is a "default constant," which provides minimum acceptable handling qualities. In normal operation, a variable gain value is determined in and provided by the flight augmentation system. The actuator position is fed back to close the loop.

Basic Roll Control—Basic roll control deflects ailerons proportional to pilot's wheel (or equivalent) rotation. The gain is either a default constant (degraded operation) or is provided by the flight augmentation system in normal operation (outboard aileron lockout accomplished by changing outboard aileron gain to zero). Actuator position is fed back to close the loop.

Basic Yaw Control—Basic yaw control deflects rudders proportional to pilot's pedal position. The gain is either a default constant (degraded operation) or is provided by the flight augmentation system in normal operation. Actuator position is fed back to close the loop.

Basic Short-Period Pitch Stability—This function deflects elevators to stabilize short-period longitudinal mode based on pitch rate and pilot's control column deflection. Control law gains are either constant (in degraded mode) or provided by the flight augmentation system in normal operation.

7.6.2.2 Flight Augmentation Processor Group

This group contains the flight augmentation processors and flight augmentation controller and performs the following:

Modify Pitch Control Characteristics—This function determines elevator deflection versus control column gain to provide satisfactory feel characteristics throughout the flight envelope. The gain value is passed to the flight essential system. This function also deflects elevators and moves the stabilizer as necessary to provide desirable pitch axis characteristics throughout the flight envelope.

Modify Roll Control Characteristics—This function determines aileron deflection versus wheel position gain necessary for good low-speed control while avoiding high-speed reversals. This function transmits this gain value to the flight essential system and also deflects the spoilers in relation to wheel rotation, autoflight commands, and flight conditions to augment roll response as appropriate for good control.

Modify Yaw Control Characteristics—This function determines rudder deflection versus rudder pedal position gain necessary for good low-speed control while avoiding high-speed loads. Gain value is provided to the flight essential system.

Enhanced Short-Period Pitch Stability—This function determines control law gains as a function of flight conditions for good performance of the short-period stability augmentation function throughout the flight envelope. Gain values are provided to the flight essential system.

Speed Mode Pitch Stability—This function deflects elevators to stabilize speed longitudinal mode based on flight measurements.

Roll-Yaw Stability—This function deflects rudders to stabilize Dutch-roll mode based on flight measurements.

Angle-of-Attack Limiting–Angle-of-attack limiting activates the stick shaker when flight conditions are close to stall and also deflects elevators to prevent the airplane from entering deep stall once the airplane begins to stall.

Wing-Load Alleviation–Wing-load alleviation deflects ailerons and flaperons to relieve gust and redistribute maneuver loads. It also deflects elevators to compensate for any pitching moment resulting from the change.

Automatic Flight Control Commands–This function deflects ailerons, rudder, elevators, and spoilers in response to commands from the autoflight system.

ACT Function Elevator Offload–This function generates stabilizer deflection signals to eliminate any steady-state elevator deflections commanded by the ACT functions.

Pitch Trim–Pitch trim moves the stabilizer in response to pilot trim switch movements, autoflight trim offload commands, and ACT function elevator offload signals based on flight conditions and column position.

7.6.2.3 Autoland Processor Group

This group contains the landing guidance processor and attitude control processor and performs the following:

Autoflight Attitude Control Loop–This function determines differences in desired and actual pitch and roll attitudes. Based on flight conditions and the autoflight mode provided by the autoflight control panel, it generates pitch and roll deflection commands to minimize differences. Autoflight commands are sent to the flight augmentation system. Desired pitch and roll attitudes are provided by either the landing guidance processor or the parameter guidance processor of the flight guidance processor group.

Autoland Rudder Control–During automatic landing, the landing guidance processor provides a crab-angle correction to be nulled at the decrab point on the approach. Rudder commands are sent to the flight augmentation system. After touchdown, the rudder commands will be generated to null differences in the lateral landing path.

Autoflight Trim Offload—During automatic control modes, this function provides stabilizer trim commands to the flight augmentation system to minimize any steady-state elevator deflection.

Autoland Path Guidance—During automatic landing modes, this function determines deviations from lateral and vertical final approach paths as defined by instrument landing system (ILS) or microwave landing system (MLS) signals and determines pitch and roll attitude commands to null the deviations. The attitude commands are given to the attitude control loop. During MLS curved or segmented approaches, path deviations are determined in the navigation processor of the flight management processor group until joining the final approach path segment. The flare vertical path guidance is also generated here.

7.6.2.4 Flight Guidance Processor Group

This group contains flight guidance processor, parameter guidance processor, and thrust control processor and performs the following:

Autoflight Thrust Control Loop—This function determines differences in desired and actual thrust (engine pressure ratio or N1) or specific energy rate input through altitude and speed (computed airspeed or Mach). It also determines autothrottle movement commands to minimize differences. The desired control parameter is determined by the autoflight system mode selected through the autoflight control panel. Autothrottle commands are sent to the autothrottle actuator and feedback commands returned to close the loop.

Parameter Guidance—Parameter guidance determines differences in desired flight parameters (selected by pilot on autoflight control panel or via column and wheel deflections) and actual flight parameters. The flight parameter to be controlled depends on the autoflight operating mode also selected on the autoflight control panel. These differences will generate pitch and roll attitude commands to be provided to the attitude control loop of the autoland processor group (heading and track, altitude, speed, attitude, and flightpath angle).

Minimum and Maximum Speed Limiting—This function ensures that the autoflight system attitude and thrust commands do not violate minimum or maximum speed limits. These limits prevent autoflight operation near stall, beyond flap placard speeds, or above maximum operating airspeed or Mach.

Flight Plan Guidance—This function determines differences in desired and actual paths. Desired path and actual data information are provided by the flight plan processor and the navigation processor of the flight management processor group. Based on the difference, this function computes heading and track, altitude, speed commands for the parameter guidance loop, and thrust control loop and provides optimization of commands as needed for total energy control.

Limit Thrust Computation—Based on flight conditions (altitude, speed, and temperature) and, if applicable, any derating parameter, it computes continuously current thrust limit (engine pressure ratio or N1) for each limit mode (takeoff and go-around, climb, continuous descent idle, approach idle, etc.).

7.6.2.5 Flight Management Processor Group

This group contains the flight plan processor, navigation data base, navigation processor, and performance data base and performs the following:

Flight Route Definition—Based on pilot entry of airport name, route identifiers, departure and arrival standard instrument departures (SID), standard terminal arrival routes (STAR), airway identifiers, navigation aid and navigation point identifiers or latitude-longitude pairs, navigation aid fixes, etc., this function creates a sequential lateral waypoint flight plan. Data entry is made through the multifunction panel. Route and navigation aid locations are stored in the navigation data base. Altitude and speed (energy) constraints, if any, will be entered by the pilot or recalled (SID and STAR) from the navigation data base.

Flight Profile Optimization—Based on performance data factors entered through the multifunction panel as well as performance modes (mininum cost and minimum fuel) for each vertical flight profile segment, the lateral flight plan with energy constraints, and current flight conditions, this function computes performance transitions and targets for each performance leg. The optimized flight profile data are then available for use by flight profile prediction and the flight guidance processor. (The profile may be reoptimized during flight when needed on a non-real-time basis. If energy or time constraints or the lateral plan is changed, reoptimization would be performed.) Optimized profile data can also be used in the navigation display. The performance data base will be used.

Flight Profile Prediction—Based on optimized flight profile, this function predicts energy, location, time, and weight (as appropriate) for each of the waypoints and performance transition points on the profile. This information can be shown on the navigation display. Computation will use the performance data base. (The prediction process may be used iteratively in the optimization process.)

Automatic Navigation—Based on initialization data entered by the pilot through the multifunction panel, body axes precision accelerometer data, and data from the attitude processor, this function computes estimated inertial position and velocity. These values are combined with very-high-frequency omnidirectional range (VOR) and distance measuring equipment (DME) measurements to provide a best estimate of position and velocity.

In MLS coverage areas, MLS angle and DME range data are combined with inertial data for the best velocity and position estimates. During MLS autoland operations before final approach, path deviation and deviation rate information are computed in compatible form for the landing guidance processor.

In automatic guidance autoflight modes, control of VOR and DME radio tuning is exercised by the automatic navigation function with information from the navigation data base. Navigation estimated position and velocity are shown on the horizontal situation display.

Navigation Data—This function provides a data base of airports, navigation waypoints, navigation radio aids, etc. Data are stored for navigation aids and waypoints, location, frequency, and identification. Route data consist of the sequence of waypoints associated with the airway, SID, STAR, etc., along with any speed or altitude (energy) constraints. Airport data may contain runway length, lighting, landing radio aid data, and terrain information. These data are used for flight plan definition, navigation display, and automatic navigation aid tuning.

Performance Data—This function provides a data base of airplane and engine performance information. The information is used in flight profile optimization and prediction and can be accessed to display equivalent "performance handbook" data such as optimum cruise altitude, endurance airspeed, engine-out driftdown speed, etc., for current conditions. Takeoff and landing data will also be available.

7.6.2.6 Pilot Flight Controls

Primary Pitch, Yaw, and Roll Inputs—This function consists of transducers that respond to wheel, column, and rudder pedal position and analog data links to the flight essential processor group. Control position data are also put on the sensor data bus.

Pilot Stabilizer Trim Input—This function detects pilot stabilizer trim commands. Commands are put on the sensor data bus.

Pilot Throttle Input—Throttle positions are measured and transmitted on the sensor data bus.

7.6.2.7 Dedicated Pitch Gyros

Pitch-Rate Sensors—Pitch-rate sensors are connected to the flight essential processor group via analog lines and are also connected through the bus terminal to the sensor data bus.

7.6.2.8 Wing Motion Sensors

Accelerometers—Accelerometers are located at proper places in the wing to measure wing accelerations for the wing-load alleviation function. They are connected to the sensor data bus.

7.6.2.9 Body Motion Sensors

Accelerometers and Rate Gyros—These gyros are located near the center of gravity (cg) to measure body rates and accelerations (inertial navigation quality) and are connected to the sensor data bus. Data are used throughout the system.

7.6.2.10 Air Data Sensors

Total Temperature Probe—This probe measures total temperature of ambient air. It is connected to the sensor data bus.

Angle-of-Attack Probe—This probe measures airplane angle of attack and is connected to the sensor data bus.

Total Pressure—This function measures total pressure of ambient airflow and is connected to the sensor data bus.

Static Pressure—This sensor measures static pressure of ambient air. It is connected to the sensor data bus.

7.6.2.11 Control Surface Position Sensors

Control surface position sensors (1) measure deflection of all elevators, rudder, and aileron surface segments; (2) measure deflection of all spoiler surfaces and trailing-edge flaps; (3) measure deflection of all leading-edge flaps and slats; and (4) measure deflection of the stabilizer. All sensors are connected to the sensor data bus.

7.6.2.12 Radio Altimeter

The radio altimeter measures altitude above the terrain and is connected to the sensor data bus.

7.6.2.13 Instrument Landing System

This system measures deviation from localizer course and glide slope and is connected to the sensor data bus. Station frequency is selected through the communication and navigation status panel through the management bus.

7.6.2.14 Microwave Landing System

This system measures deviation from runway centerline and glide slope. It also measures DME distance from the MLS station and azimuth and elevation angles relative to it. This system is connected to the sensor data bus. Final approach glide slope can be selected within limits by the pilot on the autoflight control panel. Station frequency is also selected through the management bus.

7.6.2.15 Attitude Processor

This processor uses body rate information from body motion sensors and Earth relative velocity information from the navigation processor to determine airplane attitude and true heading. Magnetic variation data stored in the navigation data base are used to synthesize magnetic heading. The attitude processor is connected to the sensor data bus and systems data bus. Orientation data are shown on the attitude director display and horizontal situation display.

7.6.2.16 Air Data Processor

The air data processor computes airspeed, Mach number, altitude, and altitude rate data using air data sensor measurements and body motion sensor measurements. It is connected to the sensor data bus. Computed data are shown on flight instrument displays. The processor uses barometric correction set by the pilot on the flight instrument display to compute barometric-corrected altitude. Altitude and altitude rate output are smoothed in a filter using vertical acceleration in normal operation.

7.6.2.17 Autoflight Control Panel

The pilot selects automatic flight modes through the autoflight control panel. These modes cover the spectrum from manual guidance and automatic control through automatic guidance and manual control (flight director) to automatic guidance and automatic control. Automatic control of the pitch, roll, and yaw axes as well as the thrust axis is engaged on this panel. In addition, various guidance modes are engaged on this panel ranging from tactical parameter tracking guidance to 4-D path-tracking guidance. Guidance parameter selections are made by the pilot on this panel. In addition, the active thrust limit mode is selected on this panel. The selected data are passed to the autoflight system on the management bus.

7.6.2.18 Communication and Navigation Status Panel

The pilot selects the frequencies of the communication and navigation radios through the communication and navigation status panel. Automatic tuning of VOR and DME by commands from the flight management processor group is also enabled, and the operating modes of the transponder and automatic direction finder (ADF) are controlled at this panel. Radio mode and frequency data are continuously displayed.

7.6.2.19 Multifunction Panel

The multifunction panel provides the interface to the pilot for initializing the navigation system and specifying the automatic flight plan and desired performance modes. Detailed performance data can be called up by the pilot on this panel.

7.6.2.20 Transponder

The transponder transmits an encoded response to air traffic control (ATC) surveillance radar interrogations depending on the mode activated by the pilot through the communication and navigation status panel. In the future, message information will also be transmitted and received during the interrogation and reply activity. The current transponder transmits an identification code and an altitude code to the ground station.

7.6.2.21 VOR and DME

VOR and DME measure bearing to and distance from the selected ground station. The station is selected manually by the pilot through the communication and navigation status panel or automatically in automatic navigation modes through the flight management processor group.

7.6.2.22 Pneumatic Sensors

Pneumatic sensors provide status of airbleeds or demand on engine system from pneumatic systems (anti-ice, pressurization, air-conditioning, etc.). The information is used to determine limit mode thrust settings and to calculate optimum performance profiles.

7.6.2.23 Engine Sensors

Engine sensors measure engine pressure ratio, revolutions per minute of rotors, gas temperature, etc.

7.6.2.24 Fuel Sensors

Fuel sensors measure fuel flow and quantity remaining in fuel tanks.

7.6.3 PRELIMINARY ARCHITECTURE DATA INTERFACES

System interface requirements are best understood by analyzing the data transfer between system elements. The data interfaces are limited to those items required to perform the top-level ACT/control/guidance functions as scoped in Subsection 6.1. Therefore, a large number of data items that will be part of the total integrated avionic system are not considered here. Three different methods of presentation are used. The first method is to tabulate the data items appearing on a data bus by the element that is the source of the data. Table 12 presents the data flow onto the sensor data bus. Table 13 shows data flow onto the systems data bus. Table 14 presents management data bus items. When large data processing elements are to be examined, a second method is used that shows the major processor elements as "sinks" and "sources" of data. Figures 25 through 30 present data transfer information organized in this way, with arrows indicating major data flow.

Finally, the data interfaces are described by showing the elements required to perform the high-level functions. Previously, output from the top-down analysis of the airplane functional requirements was presented (sec 6.0) as a list of high-level functions in tabular form. The data interfaces for most of these high-level functions now appear in Figures 31 through 53. As an example, the function "modify pitch control characteristics" is presented as Figure 35. These single-thread diagrams are useful when determining how the architecture will perform a particular high-level function.

Table 12. Sensor Bus Data Items

Sensor bus interface	Bus data item
Pilot flight controls	Column deflection Wheel deflection Rudder pedal deflection Stabilizer trim command Throttle position
Dedicated pitch gyros	Pitch rate
Wing motion sensors	Wing acceleration
Body motion sensors	Body accelerations X acceleration Y acceleration Z acceleration Body angular rates Angular rate about X axis Angular rate about Y axis Angular rate about Z axis
Air data sensors	Indicated static pressure Total pressure Total air temperature Indicated angle of attack Indicated impact pressure
Surface position sensors	Elevator segment deflection Aileron segment deflection Rudder segment deflection Spoiler panel deflection Trailing-edge flap segment deflection Leading-edge flap and slat segment positions Stabilizer deflection
Radio altimeter	Height above terrain
Instrument landing system	Localizer deviation Glide slope deviation
Microwave landing system	Azimuth deviation Elevation deviation Range to station Azimuth angle Elevation angle
Air data processor	Airspeed Corrected angle of attack True airspeed Mach number Altitude rate (smoothed) Airmass flightpath angle Pressure altitude (smoothed) Barocorrected altitude (smoothed)
Engine sensors	Engine pressure ratio (EPR) Low-speed-rotor speed (N1)
Attitude processor	Pitch attitude angle Roll attitude angle Pitch attitude rate Roll attitude rate Magnetic heading True heading Heading rate

Table 13. Systems Bus Data Items

Sensor bus interface	Bus data item
VOR/DME	Bearing to station Range to station
Pneumatic sensors	Airbleed status (on/off status of systems with significant bleed air demand)
Fuel system	Fuel flow rate Total fuel quantity
Autothrottle actuator	Autothrottle position Autothrottle actuator rate
Autoland processor group	Elevator deflection command Roll deflection command Rudder deflection command Stabilizer trim deflection command
Flight guidance processor group	Guidance pitch reference Guidance roll reference Autothrottle command
Flight management processor group	Flight plan Current track Current airspeed Current thrust mode Current altitude Flight plan Next track Next airspeed Next thrust mode Next altitude Flightpath angle Acceleration along flightpath Acceleration normal to flightpath Ground track Ground speed MLS path deviation—lateral MLS path deviation—vertical MLS path distance Vertical acceleration Cross-track acceleration North velocity East velocity Latitude Longitude Along-track acceleration Wind speed Wind angle

Table 14. Management Bus Data Items

Management bus interface	Bus data item
Autoflight control panel	Selected runway heading Selected MLS glide slope Selected maximum bank angle Selected autoflight mode Selected heading and track Selected airspeed and Mach No. Selected limit thrust mode Selected thrust derate Selected altitude Selected flightpath angle
Multifunction panel	Interactive navigation initialization data Interactive flight plan definition data Interactive performance mode definition data Interactive prediction and performance data requests
VOR/DME	Tuned station frequency
Instrument landing system	Tuned station frequency
Microwave landing system	Tuned station frequencies (MLS and DME) Reference glide slope angle
Communication and navigation status panel	VOR/DME selected frequency ILS selected frequency MLS selected frequency Transponder mode select Transponder identification code select VHF communication selected frequency HF communication selected frequency
Baroset control	Barometric altimeter setting
Flight management processor group	Interactive navigation initialization requests Interactive flight plan definition requests Interactive performance mode definition requests Interactive prediction and performance data Magnetic variation Autotune VOR/DME selected frequency
Transponder	Operating mode Identification code

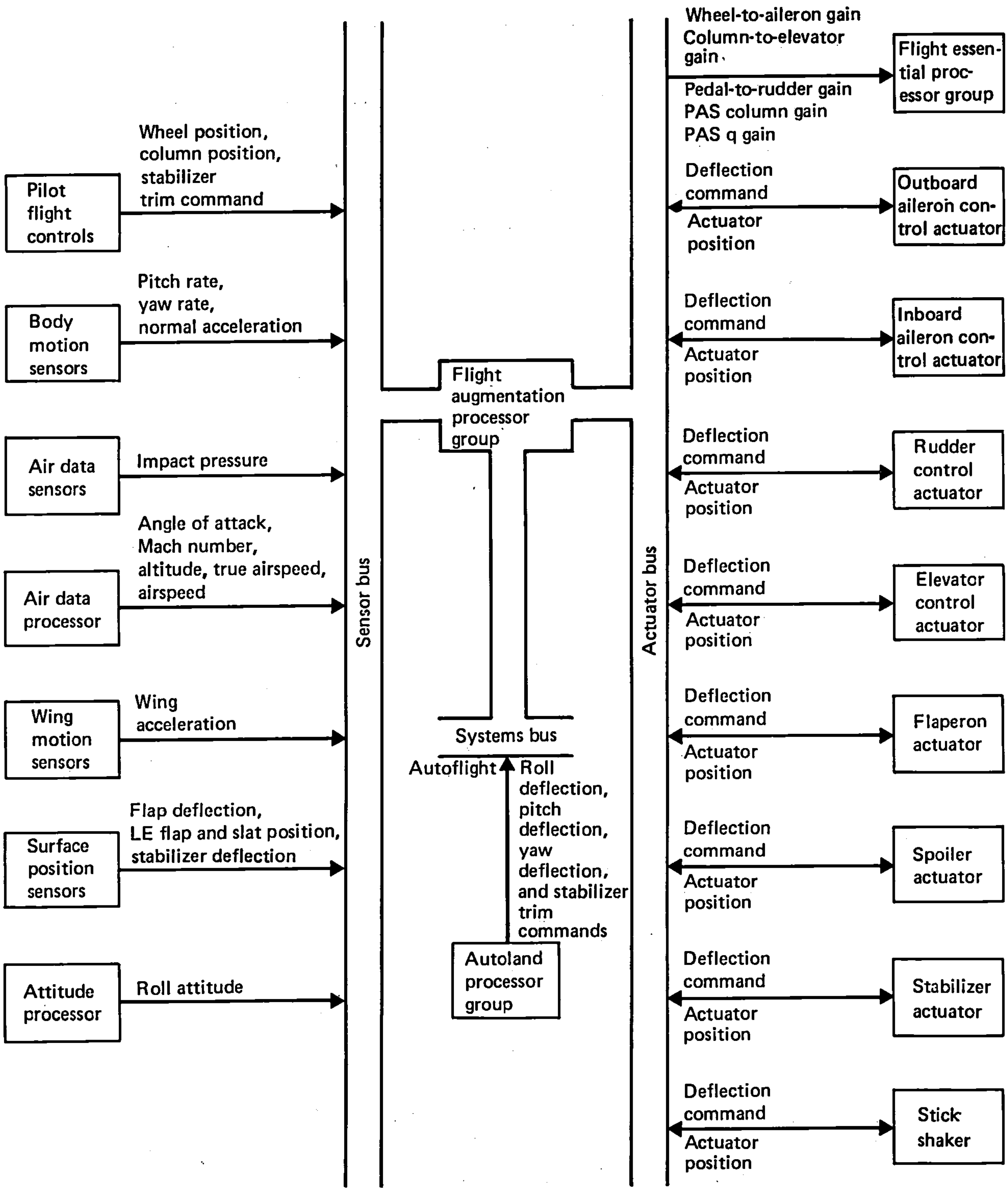


Figure 25. Flight Augmentation Processor Group Data Transfer

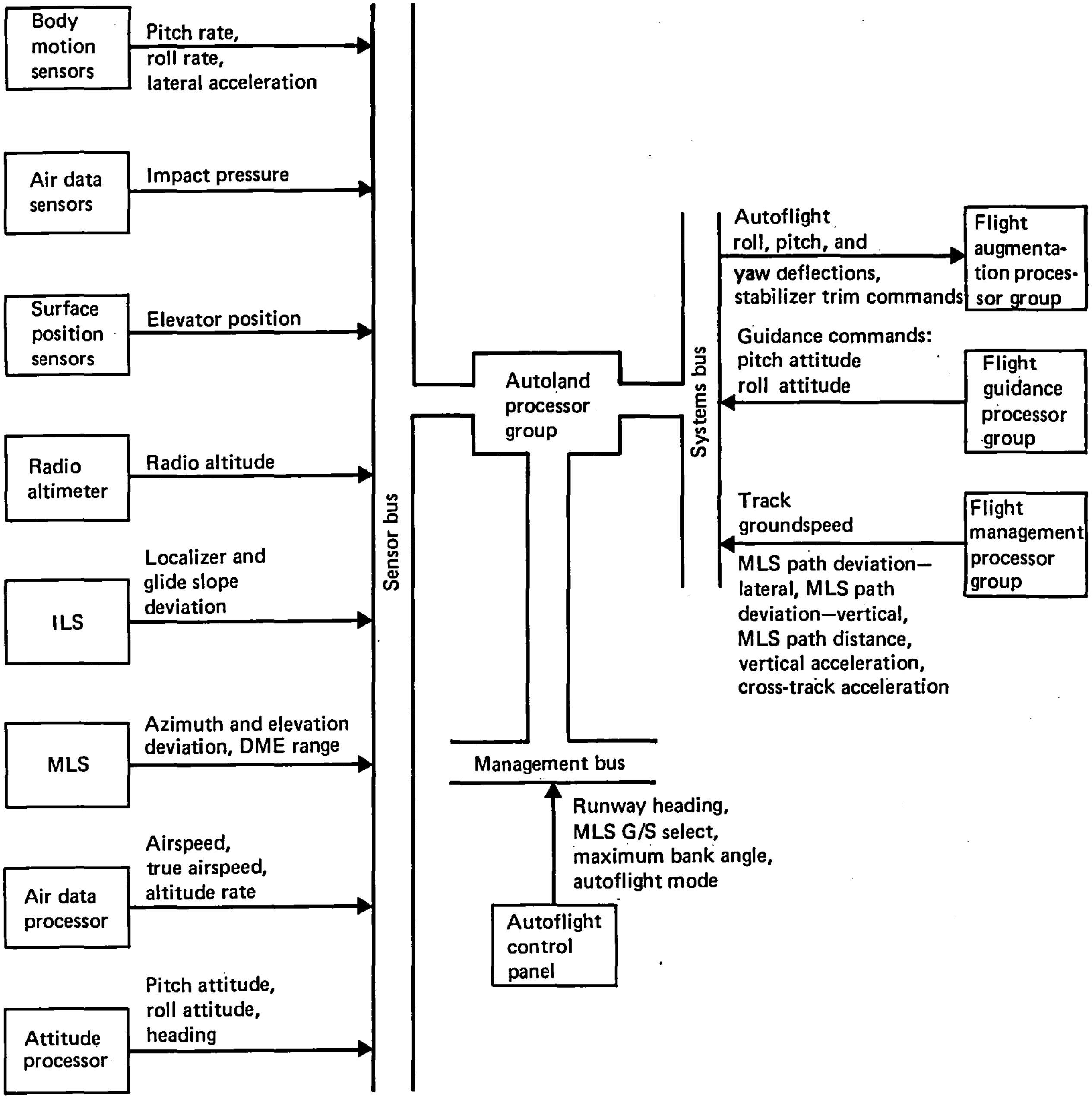


Figure 26. Autoland Processor Group Data Transfer

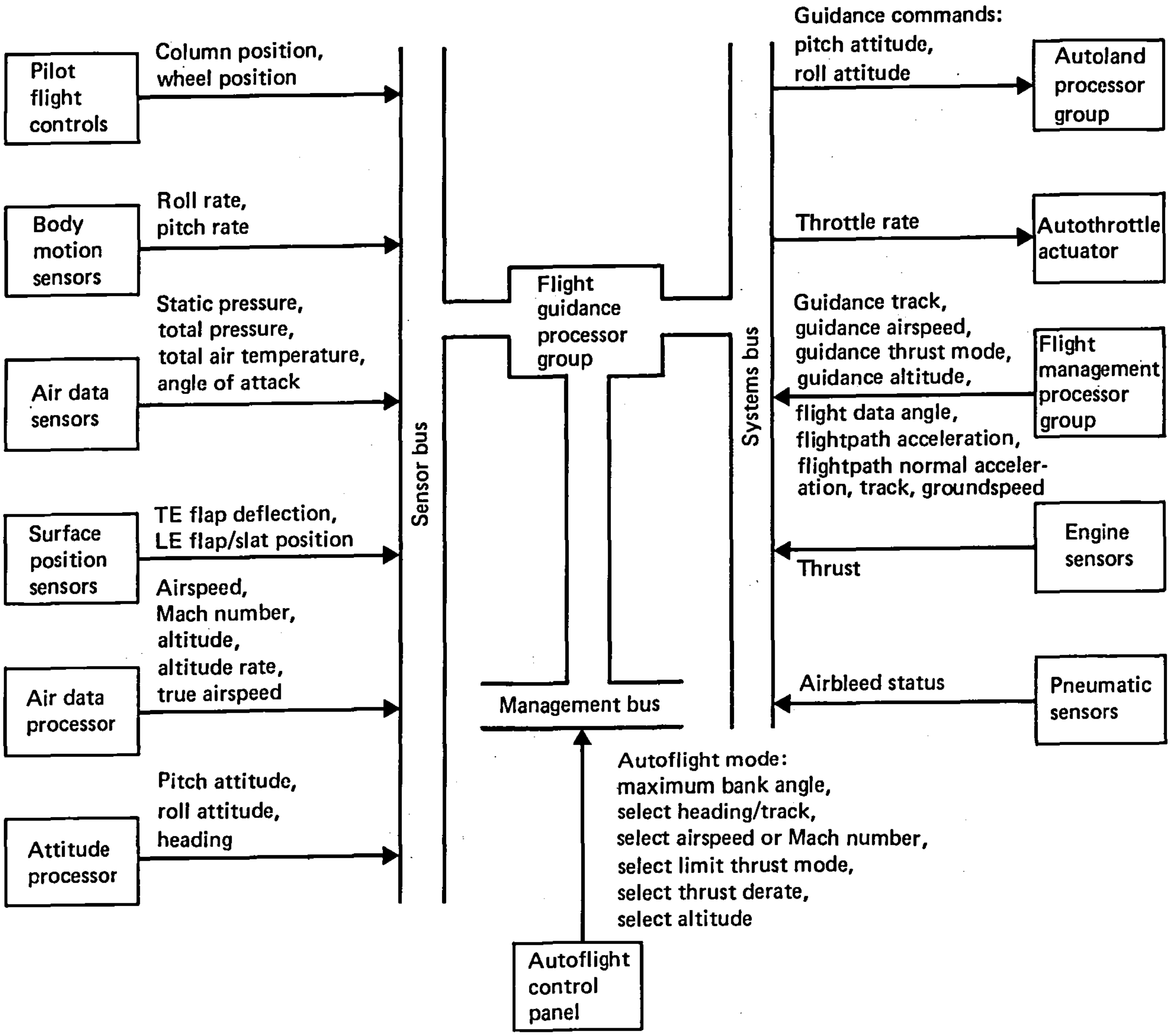


Figure 27. Flight Guidance Processor Group Data Transfer

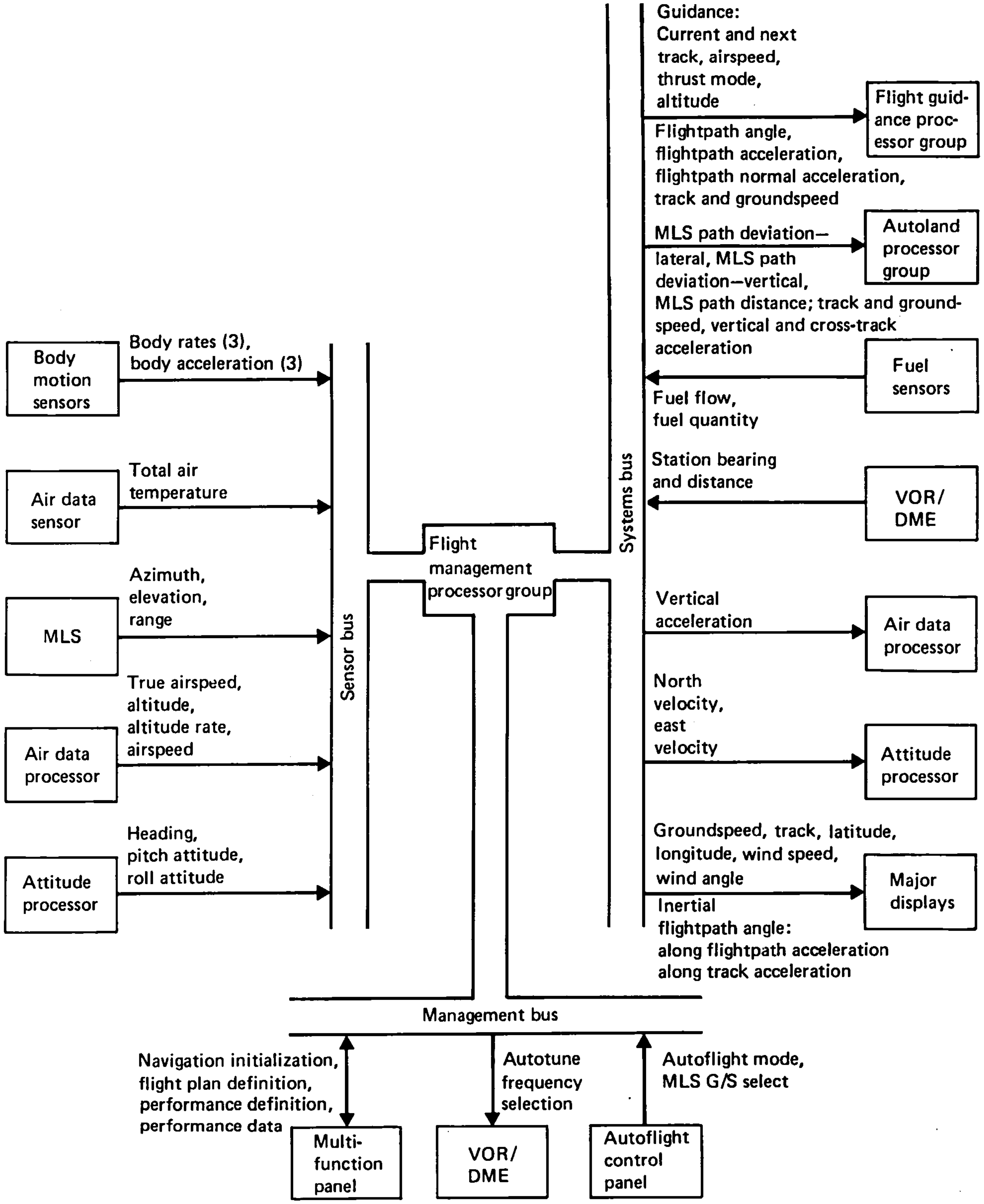


Figure 28. Flight Management Processor Group Data Transfer

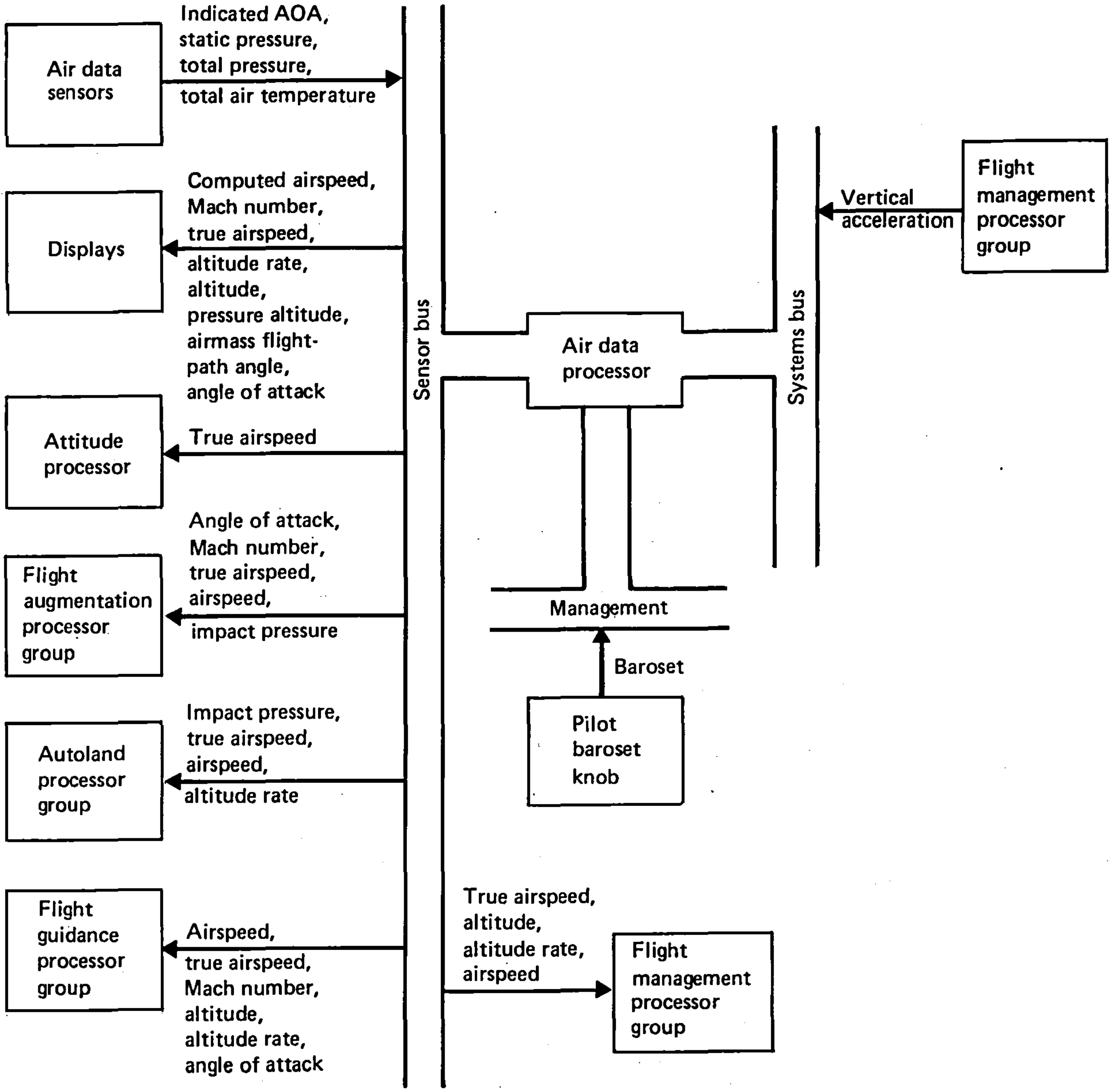


Figure 29. Air Data Processor Data Transfer

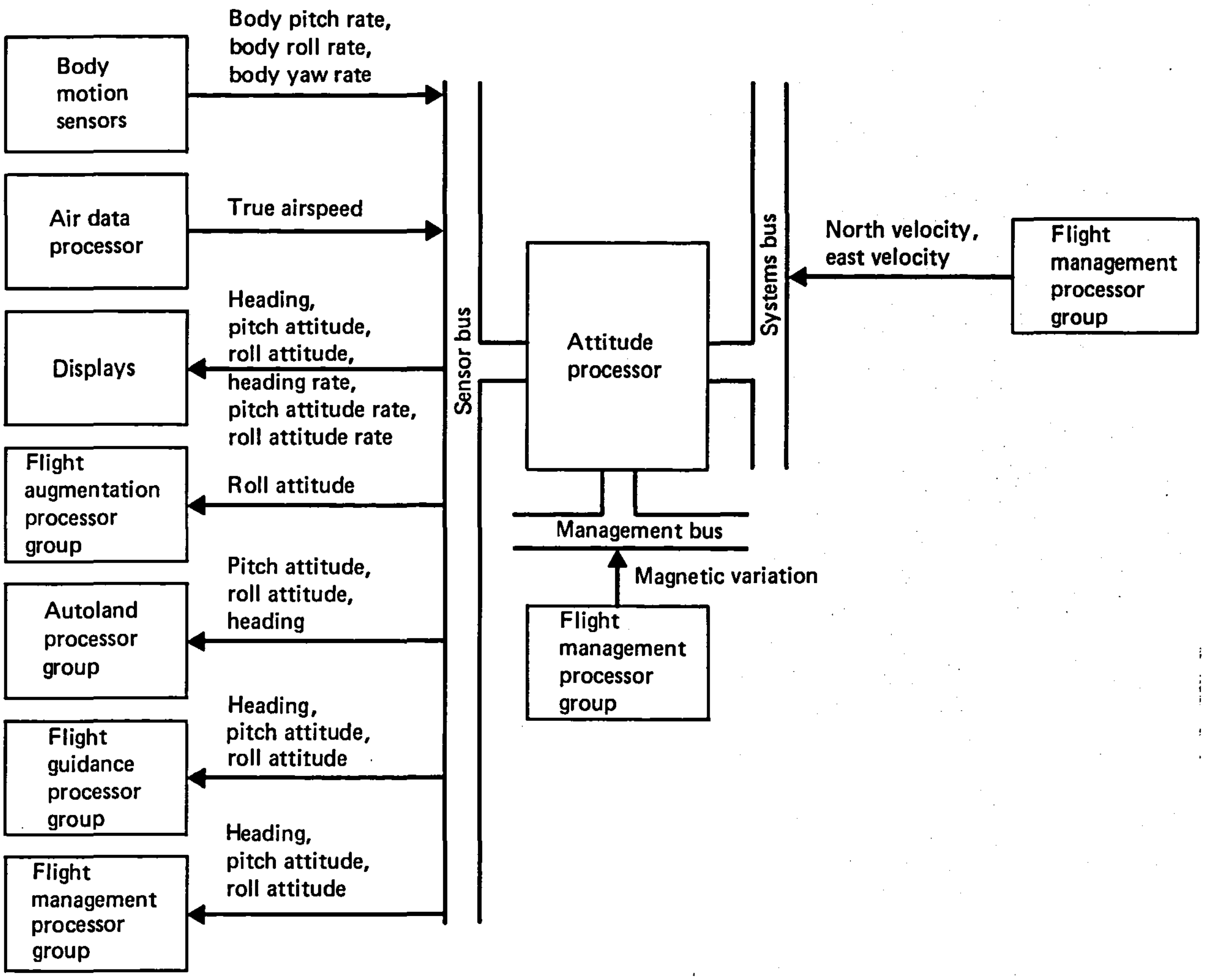


Figure 30. Attitude Processor Data Transfer

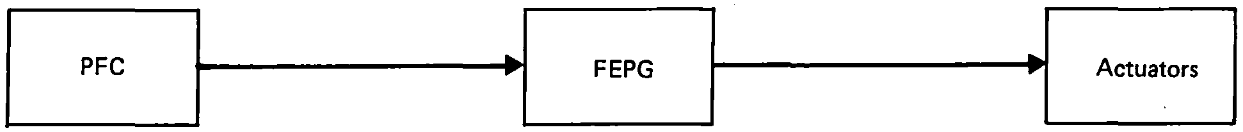


Figure 31. Change Pitch Attitude via Column Deflections

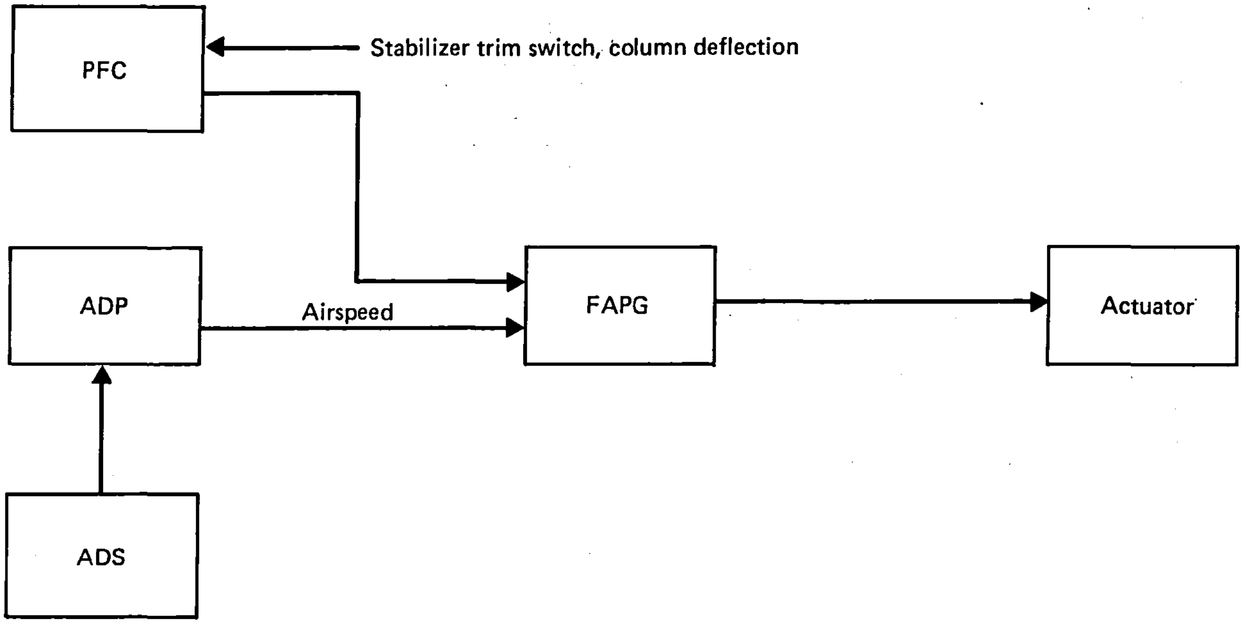


Figure 32. Adjust Pitch Attitude Trim

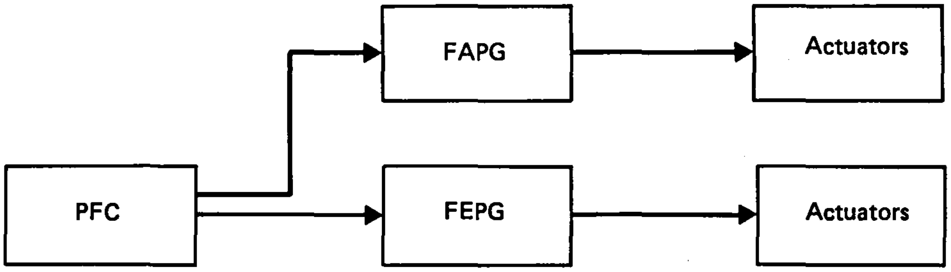


Figure 33. Change Roll Attitude, Using Wheel Deflections to Ailerons Through Essential Processor and Through Augmentation Processor to Spoilers

Figure 34. Change Sideslip Angle via Rudder Deflections, Using Rudder Pedals

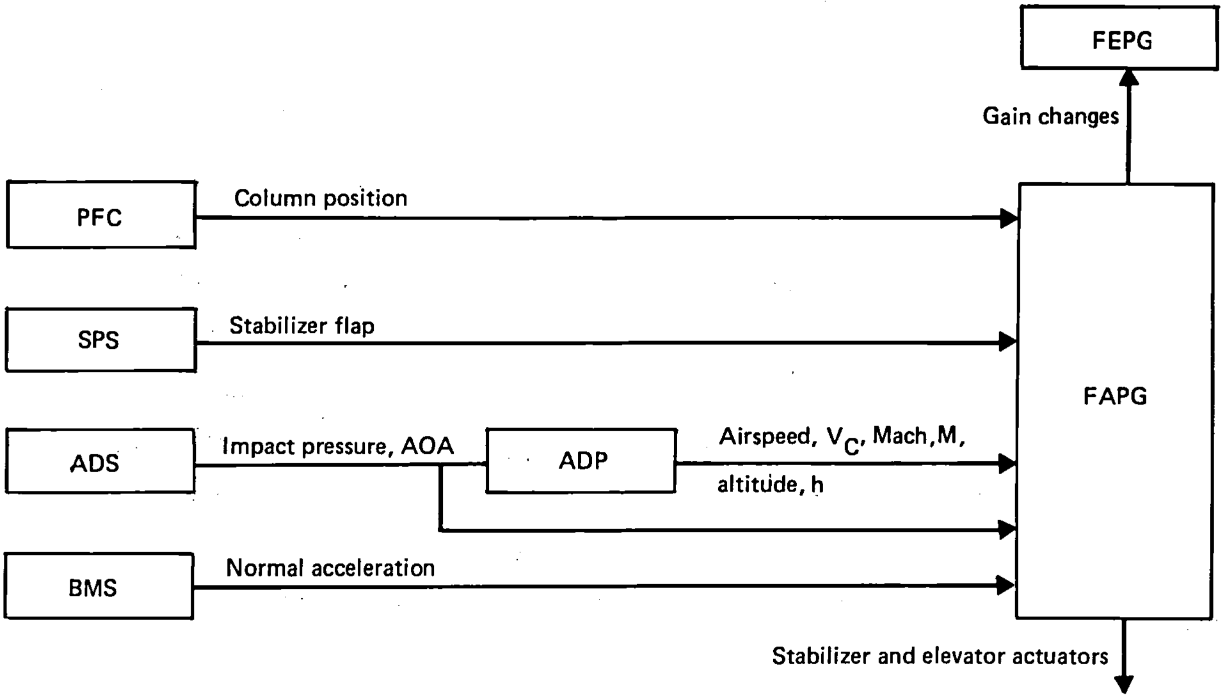


Figure 35. Modify Pitch Control Characteristics

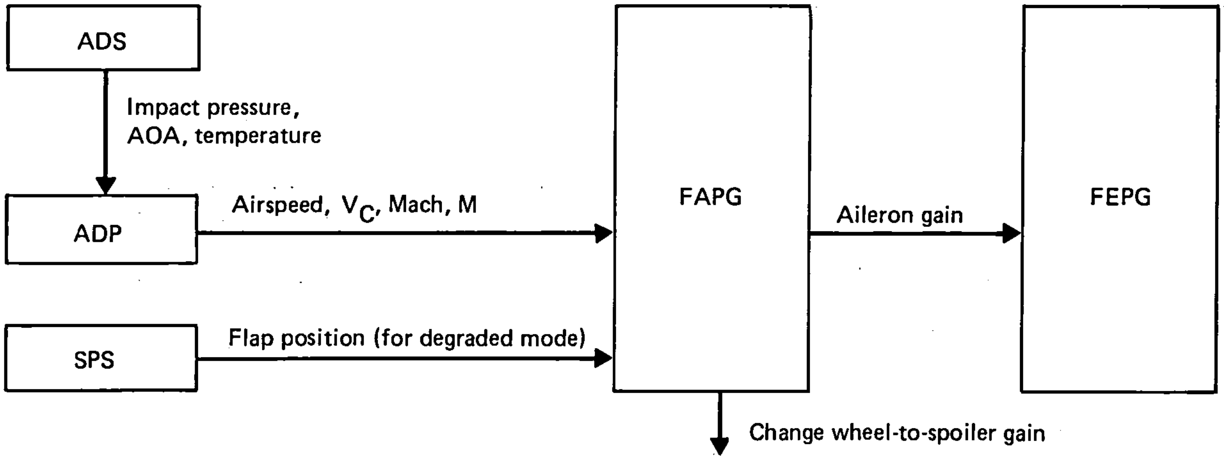


Figure 36. Modify Roll Control Characteristics

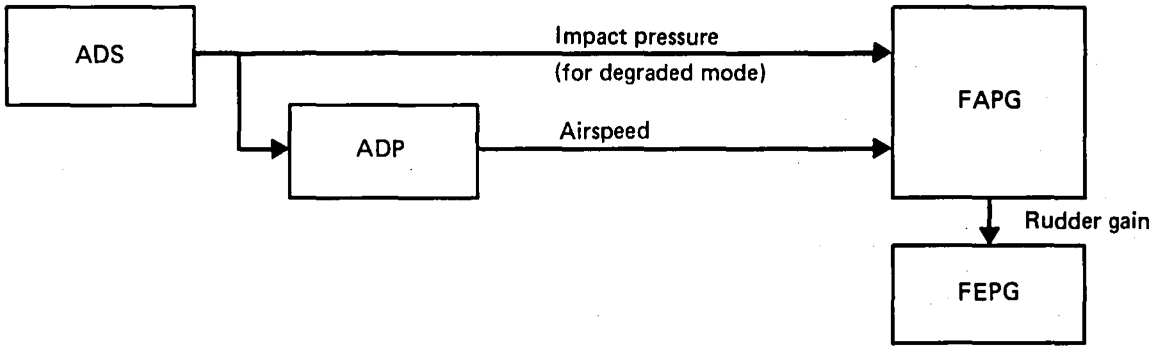


Figure 37. Modify Yaw Control Characteristics

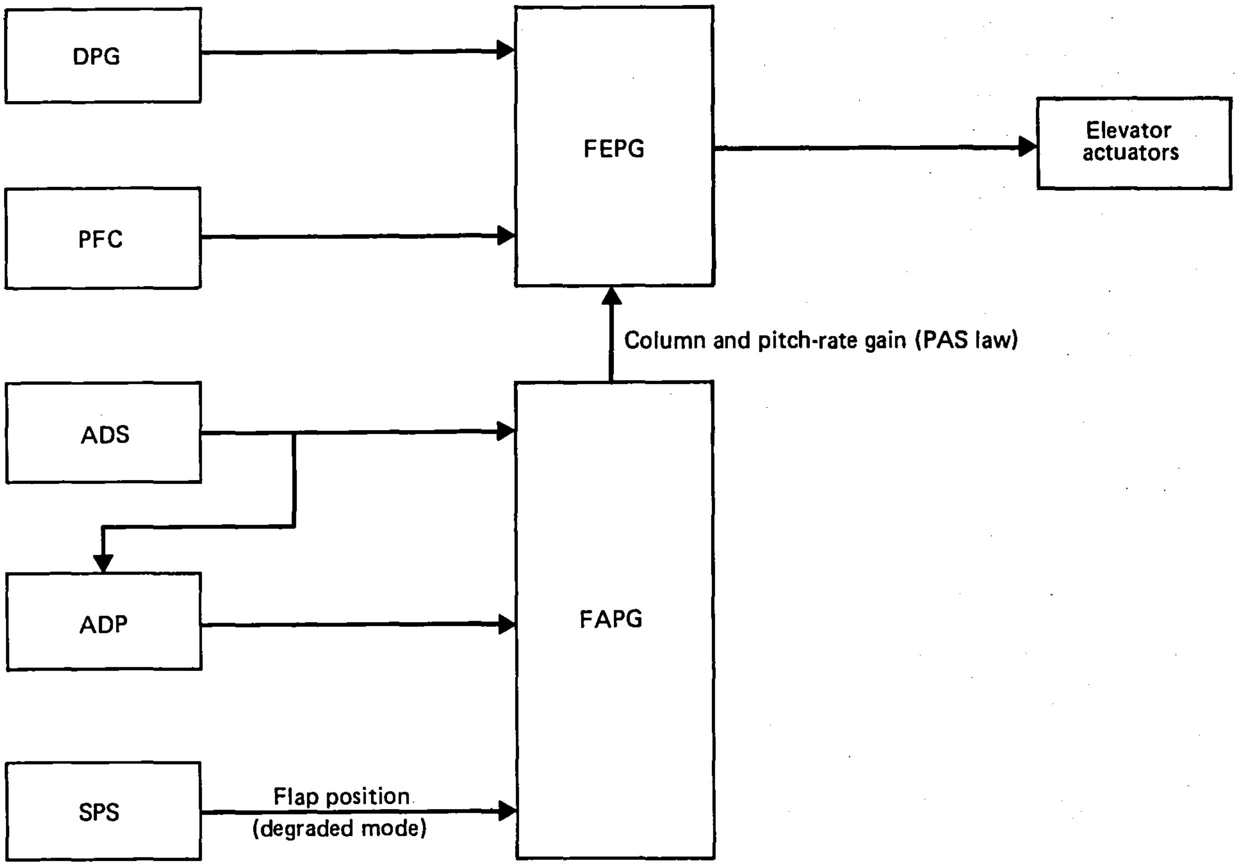


Figure 38. Augment Stability—Pitch-Axis, Short

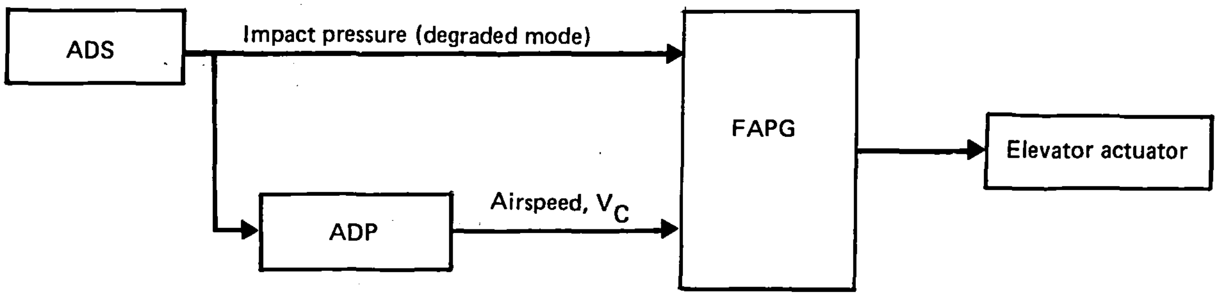


Figure 39. Augment Stability—Pitch-Axis, Speed

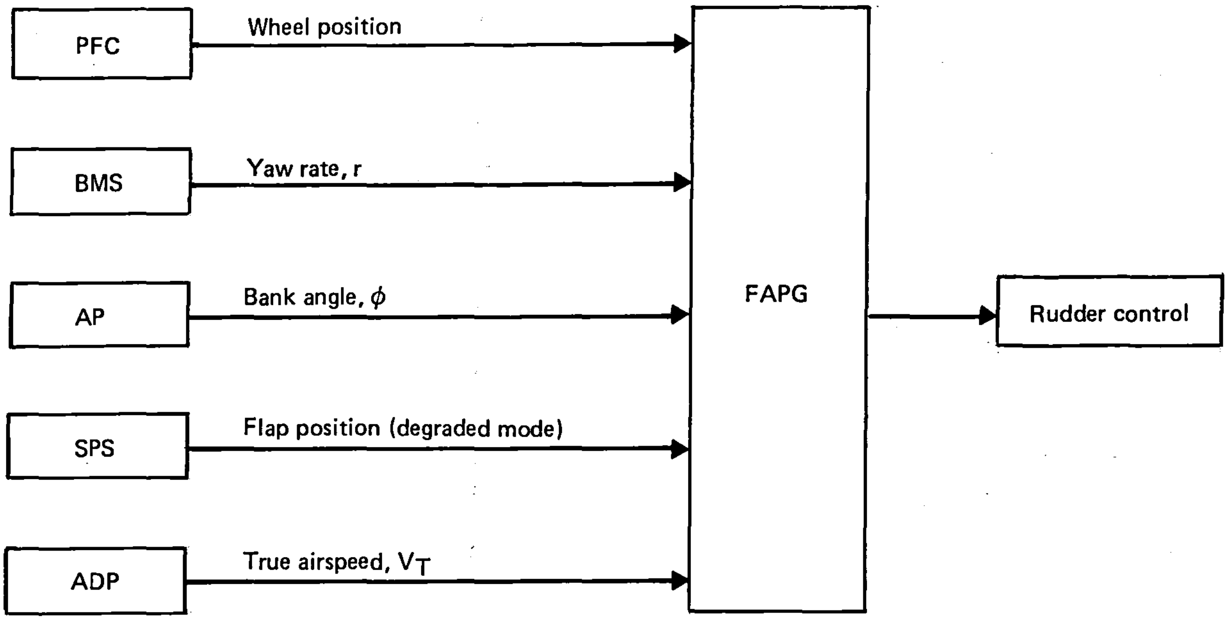


Figure 40. Augment Stability—Roll and Yaw Axes (Lateral/Directional-Augmented Stability)

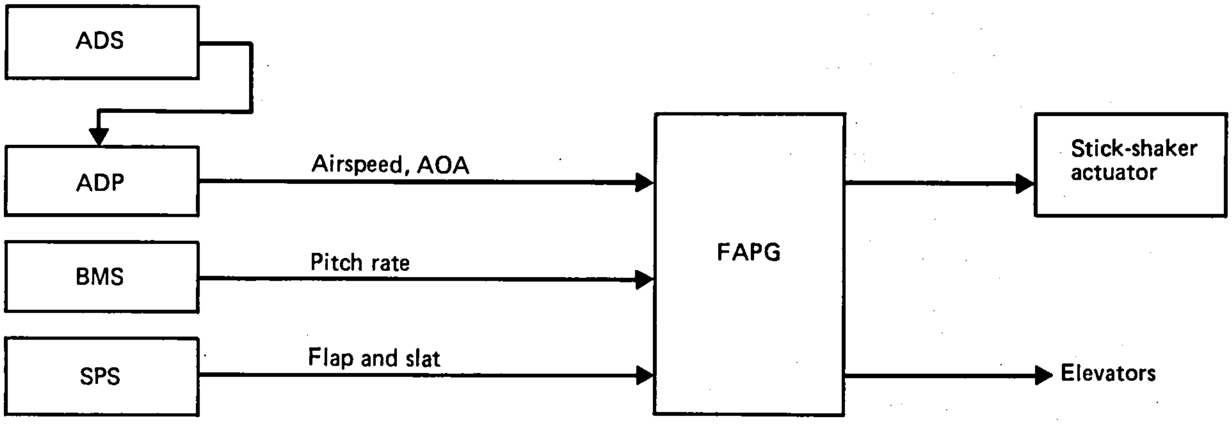


Figure 41. Limit Angle of Attack

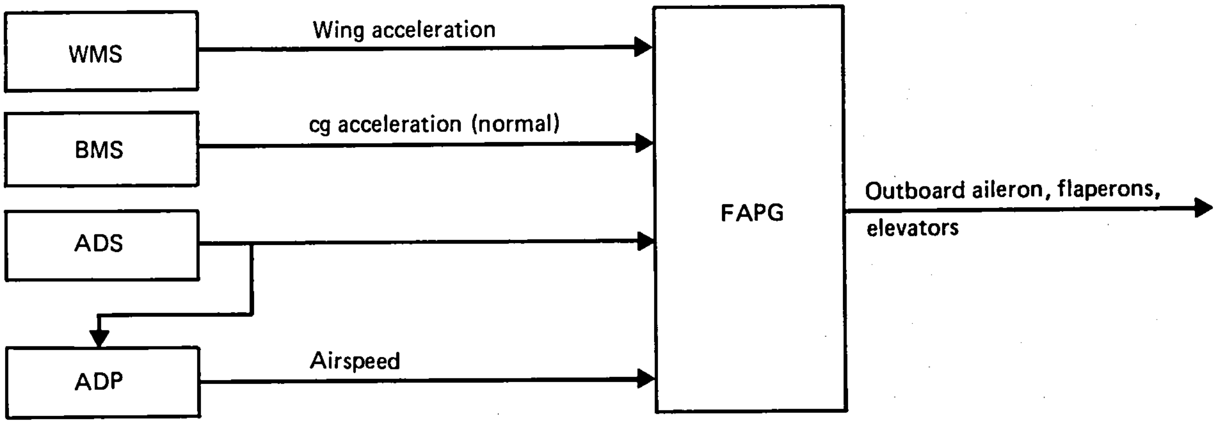


Figure 42. Relieve Structural Loads (Wing-Load Alleviation)

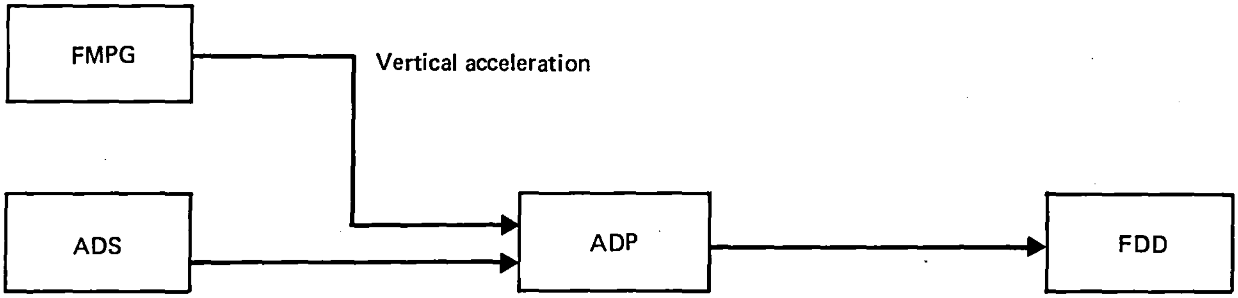


Figure 43. Display Airspeed and Mach, Altitude, and Vertical Speed

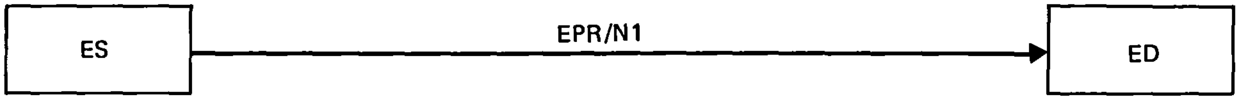


Figure 44. Display Engine Thrust

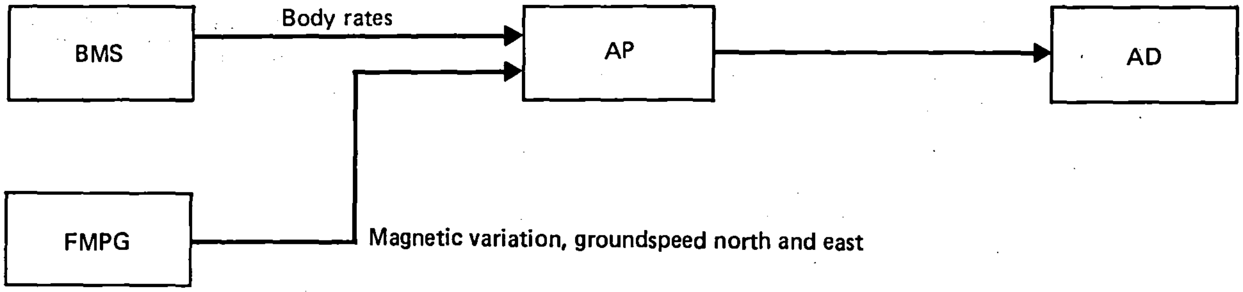


Figure 45. Display Attitude, Pitch and Roll, and Direction

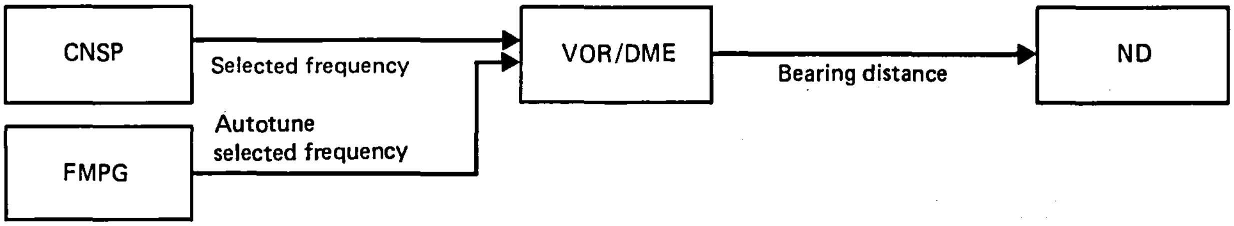


Figure 46. Display Bearing and/or Distance to Navigation Aids

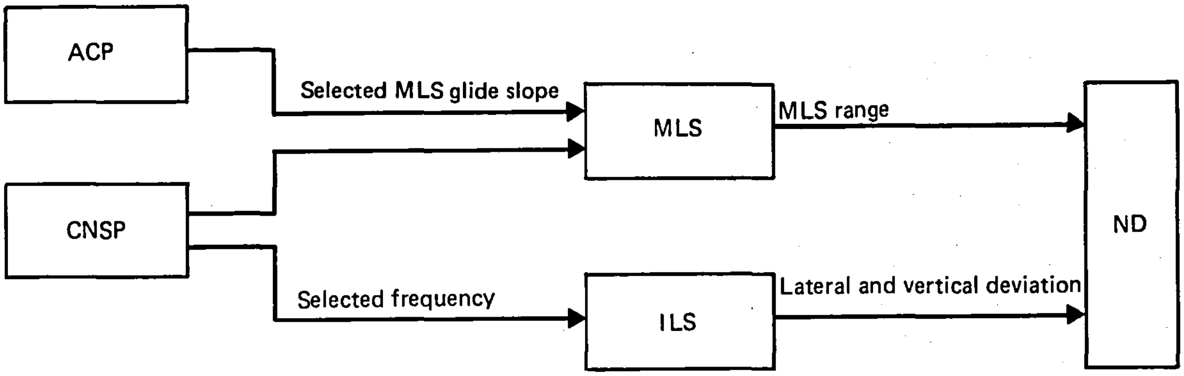


Figure 47. Display Deviation From Selected Landing System Path

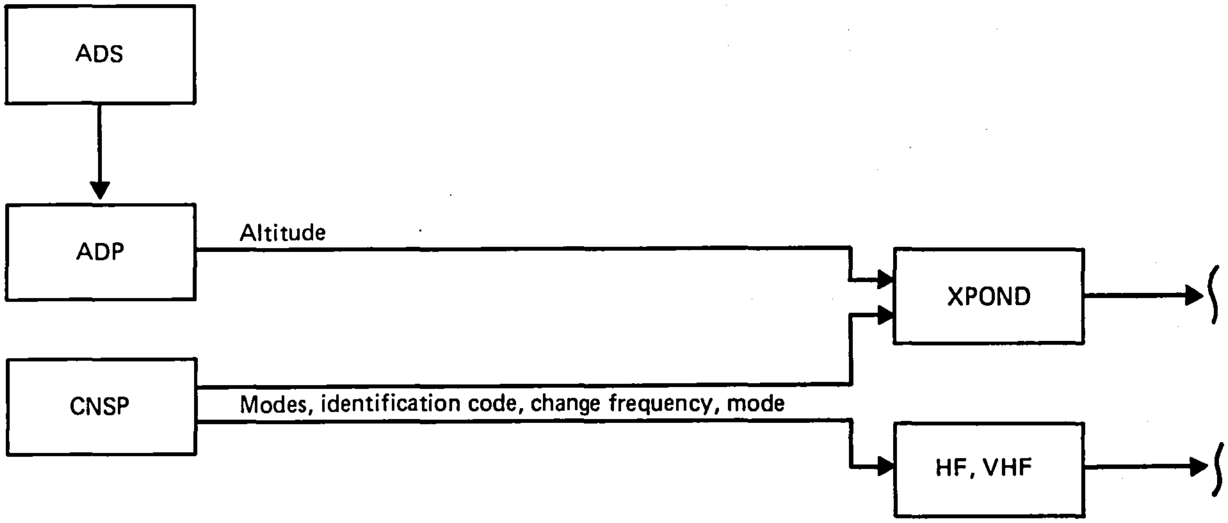


Figure 48. Communications

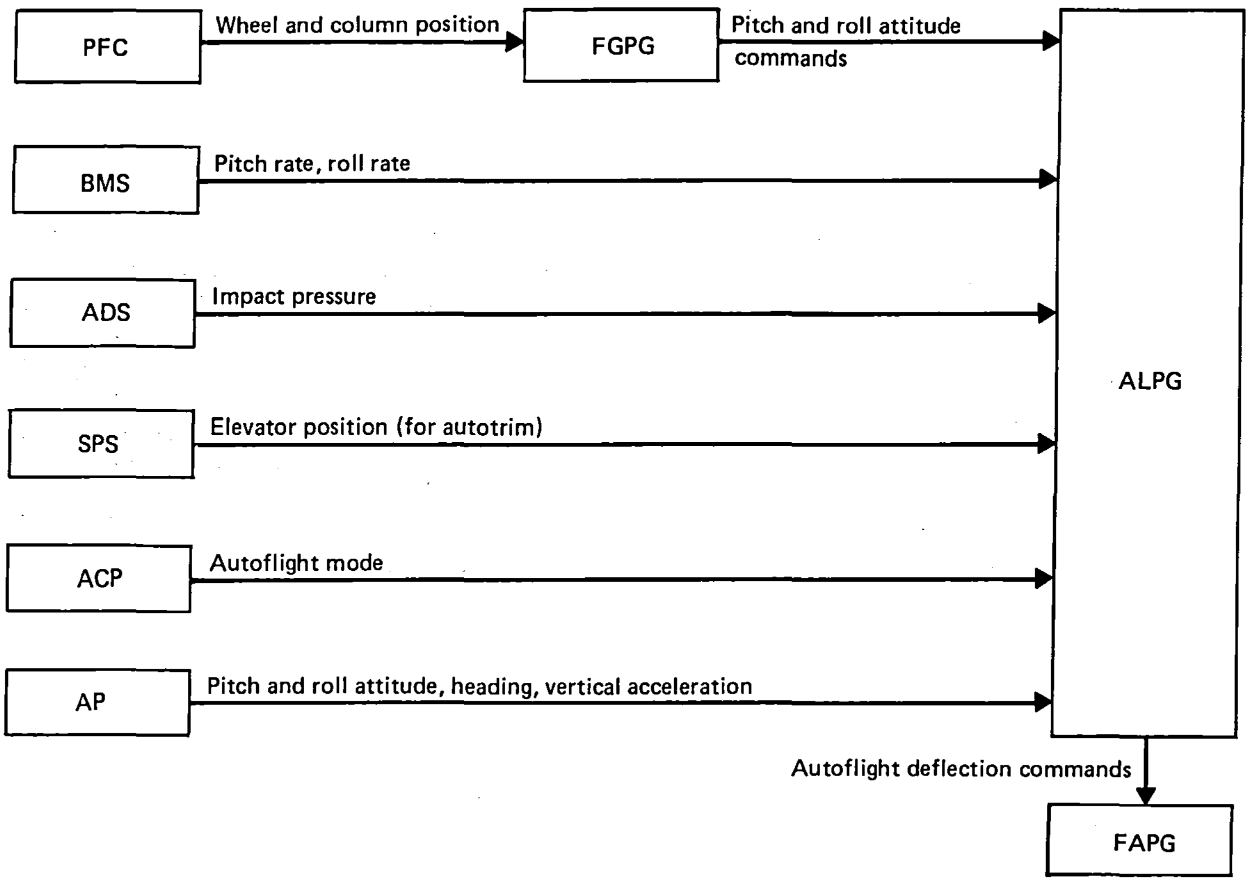


Figure 49. Pilot-Assisted Steering

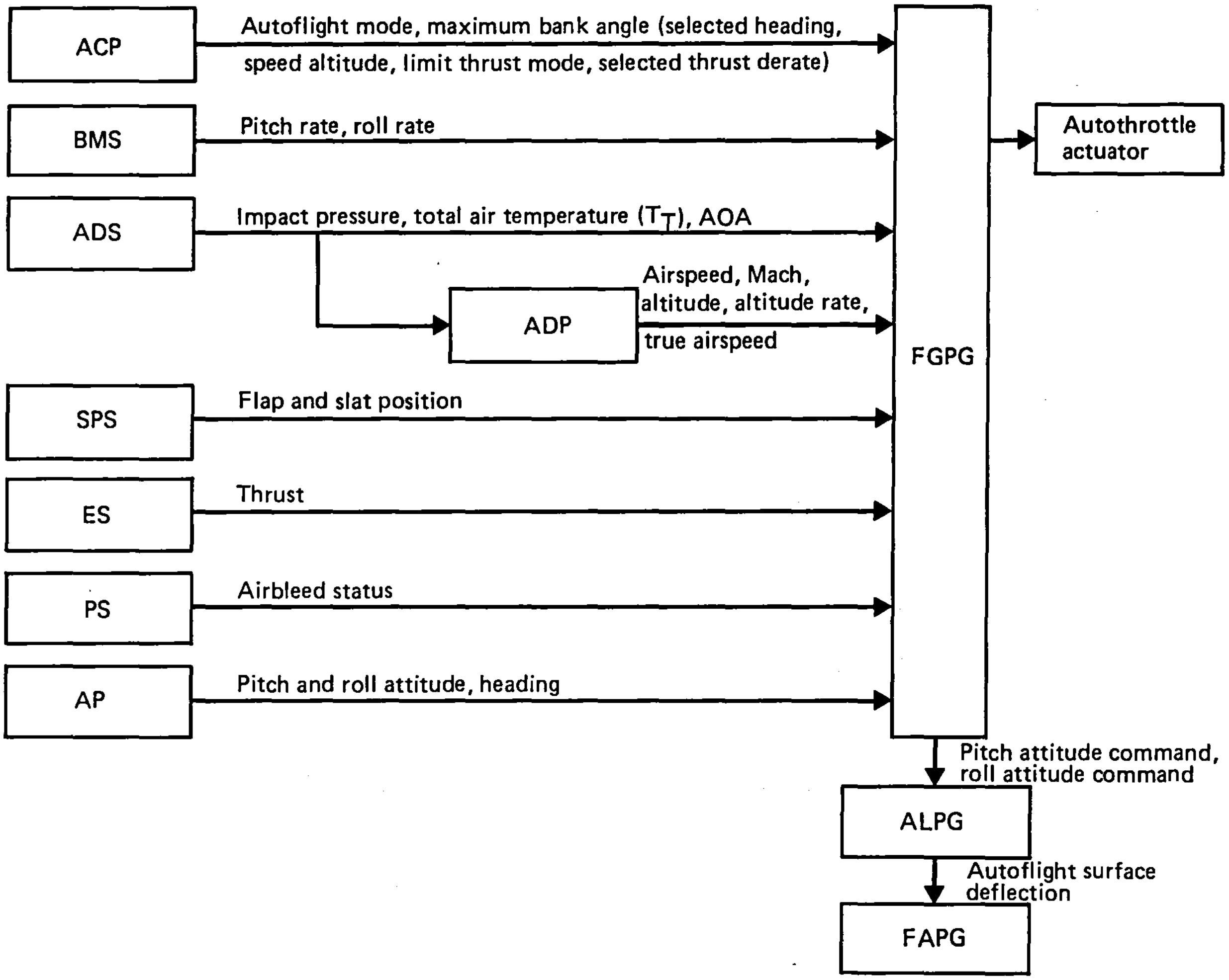


Figure 50. Capture and Maintain Flight Parameters (Including Minimum Speed and Maximum Speed)

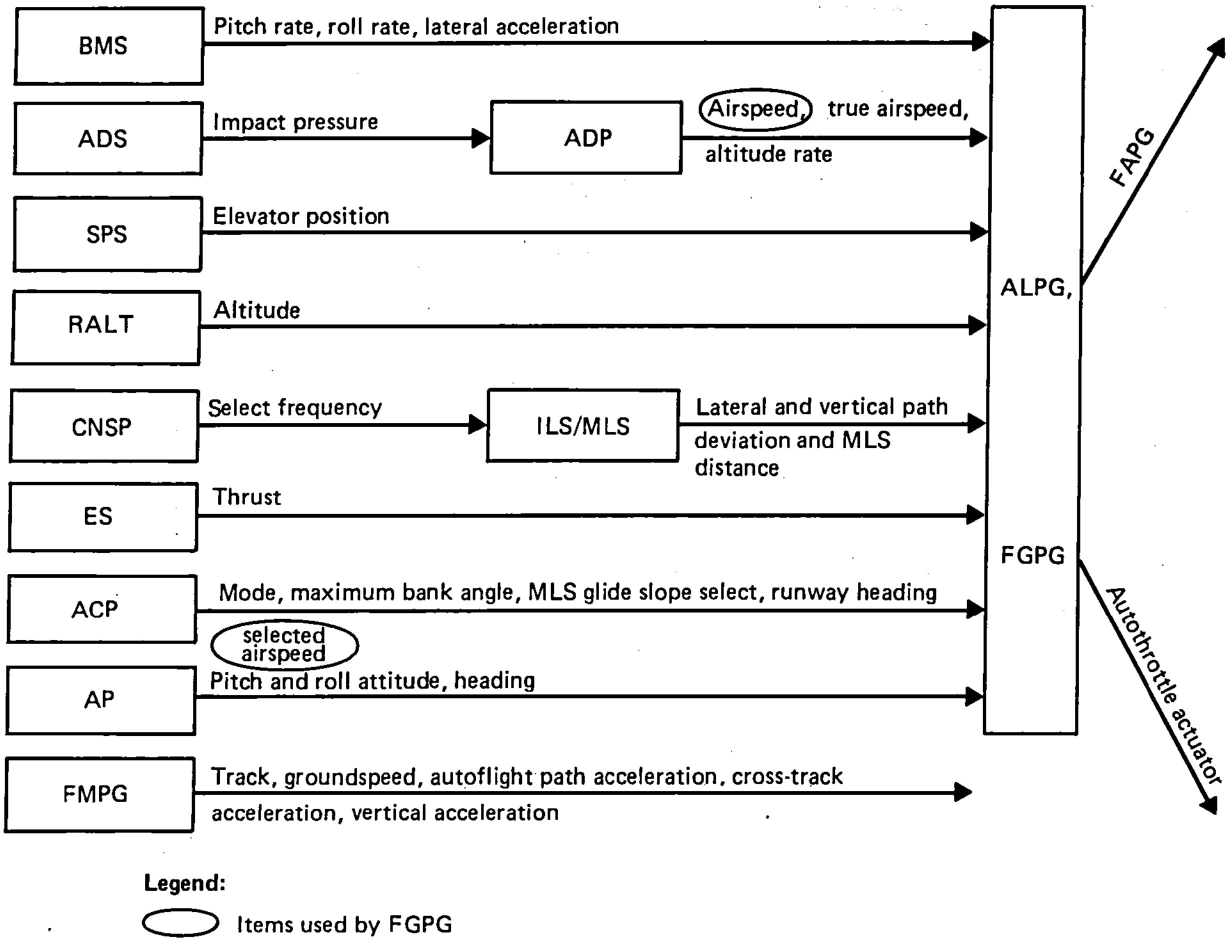


Figure 51. Capture and Track Landing System Path

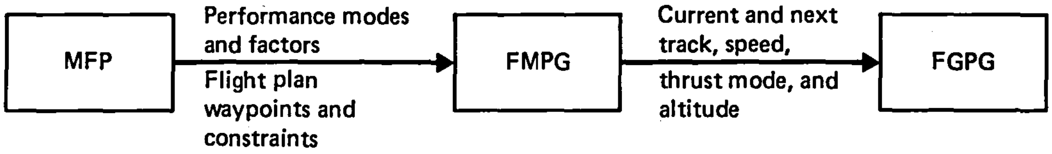


Figure 52. Provide Flight Parameter Targets To Follow Optimal Flight Profile

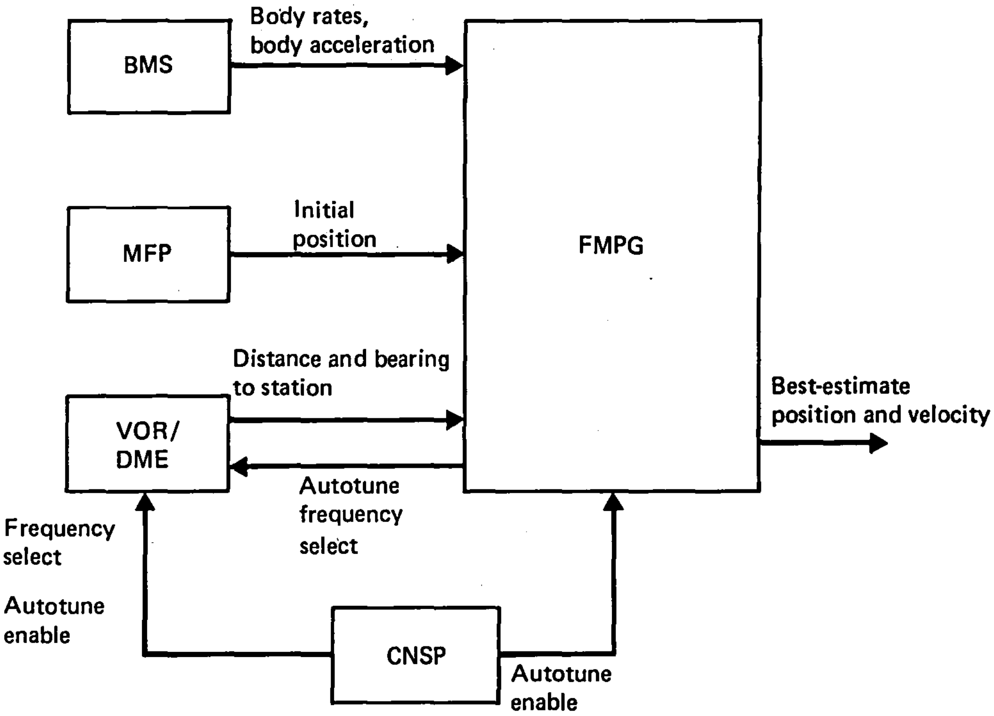


Figure 53. Determine Airplane Position and Velocity

7.6.4 ALTERNATIVES TO PRELIMINARY ARCHITECTURE

This section discusses alternatives to some of the designs and approaches shown in the preliminary architecture. Qualitative effects of the alternatives on the preliminary architecture are described to point out some of the obvious benefits and limitations.

The assumed actuator interface strongly influences the architecture. In the preliminary architecture, each elevator, rudder, and aileron surface has three sets of redundant actuators. The physical complexity of this configuration is significant. The fundamental problem in the Initial ACT Configuration actuator interface is how to share the control surface between the crucial manual control functions, the critical active control functions, and the workload relief autopilot functions. This sharing must be done so that a malfunction in a less critical function does not jeopardize the more critical functions.

In the preliminary architecture, separation is performed by using basically one set of secondary actuators for the crucial functions and another set of secondary actuators for the critical and workload relief functions. Both sets of secondary actuators provide inputs to the power actuators that deflect the surfaces. The secondary actuators for the less critical functions will have limited authority compared with the actuators used for crucial functions if the requirements of the specific functions involved permit this.

A method for combining surface deflection commands from sources of different criticality must be found if the secondary actuators are to be eliminated. This method must provide the same subsystem integrity and level of fault tolerance as that of the secondary actuators. In the replacement system, the combining function (which would include fault checking or voting) probably would be performed in an element of the most critical subsystem. Therefore, eliminating the secondary actuators requires adding processing functions to the more critical system. The replacement method would require a thorough development effort because of the criticality of the functions involved.

The crucial functions of the preliminary architecture are implemented in the flight essential system. To provide a "get home" capability, these functions use basic control laws that operate with a fixed gain and with a minimum number of inputs. Keeping the system processing limited and well isolated from other functions is an attempt to simplify the system design and ease the difficulty of the verification and validation effort. With this approach, a generic fault in the crucial system can lead to loss of the airplane. Therefore, generic faults must be eliminated from the crucial system during development prior to flight test.

An independent backup system is an alternative design that would somewhat alleviate the generic failure concern. The existence of the backup system should in no way reduce the crucial system design, development, and verification effort. The backup system might only be installed for the duration of the flight test effort, and it might be removed after certification of the crucial system. Therefore, it should be designed so that its removal has no effect on the rest of the system. The backup system would provide basic get-home flight control capability. The problem introduced by the alternative design is how to switch control from the normal system to the backup system. The switching would take place only to prevent a catastrophic occurrence, and the probability of false alarm switching must be insignificant. To satisfy these requirements, an intelligent switching function or system monitor is necessary.

In an installation requiring a backup system, the status of the backup system would influence flight dispatch. Loss of capability would cause dispatch refusal or flight diversion. If the backup system were always in an active status, the system monitor could be used to check system status. With this feature, the monitor would listen to the input and output data for both the essential system and the backup system. The monitor would provide a signal to switch actuator command control from the essential system to the backup system in the event of failure.

With incorporation of a simple backup system, the design rules for the essential system might be modified. The essential system could be upgraded to perform all normal modes of the top-level crucial functions. This would require additional sensor input data and more data processing in the essential system. In addition, the essential system would have to incorporate degraded mode capability to handle the loss of noncritical sensor data.

This increase in essential system functional effort would eliminate the interface between the essential and augmentation systems. Figure 54 shows the alternative approach. Incorporation of a backup system presents a major design challenge. The crucial switching function is in itself suitable for a separate development effort.

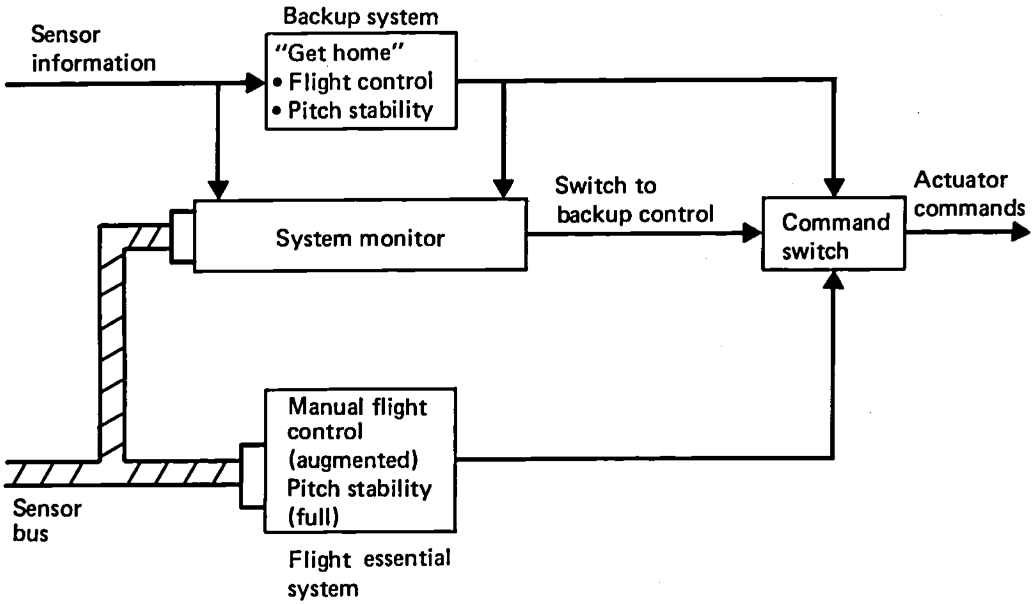


Figure 54. Backup System Configuration

The actuator interface for the rudder surfaces is identical to that for the elevator and aileron surfaces in the preliminary architecture. However, criticality analysis of the top-level functions indicates that yaw control is not as crucial as roll and pitch control from a safety standpoint. With this in mind, manual control of the rudder could be reallocated to the augmentation system from the essential system. The actuator interface for the rudder would be simplified by eliminating the secondary actuators. The change would simplify the actuator interface and the computing functions of the essential system but would require adding more computing functions to the augmentation system.

The preliminary architecture presented earlier does not use "smart" actuators. Only signal conditioning and digital bus interface functions are mandatory at remote locations in the preliminary architecture. With a "smart" actuator, some system intelligence is located in the harsh environment of the actuators. Not only is the environment for this intelligence more difficult than that of the normal electronics equipment bay, but its accessibility for maintenance is degraded. Currently, development efforts are under way to relieve these concerns. Local intelligence at the actuator can be used to close servo loops and perform some levels of fault tolerance at the actuators. These functions could use redundant feedback sensors on the actuator and suitable computation and selection logic at that point. The "smart" actuator could also use multiple, ruggedized microprocessors to provide redundant internal loop closure computation and response.

Data processing functions are shared extensively in the preliminary architecture. In the same way that top-level functions share sensors and actuators, outputs of certain common data processing functions are also shared. Processes such as calculating airplane attitude, airplane speed, and surface deflections necessary to automatically maintain attitude are performed at one location in the system. The criticality of these shared processing functions is therefore determined by the most critical top-level function.

An alternative would be to duplicate these common data processing functions in each top-level function. In this approach, the attitude display function would calculate attitude independently of the attitude calculation for the autopilot functions. This nonshared alternative leads to subsystems that are more autonomous at the price of duplicated processing functions throughout the system. Final or intermediate results of top-level functions would not be shared with other top-level functions. The nonshared alternative requires each subsystem to perform more data processing functions and increases the relative size of the subsystems. The additional design and verification and validation effort implicit in this alternative might be alleviated if common software functions could be maintained in a library and implemented in subsystems separate from the library. This also implies compatible—if not identical—computing hardware. Figure 55 shows an example of the alternatives.

In the preliminary architecture, the ARINC 700 inertial reference system functions are partitioned into three elements: body motion sensors, attitude processor, and navigation processor. The motivation for this split is that the inertial reference system typically serves several top-level functions that have different criticality ratings. Design ground rules and redundancy can be specified separately for the three element types as necessary to meet the reliability requirements of the top-level functions. The body motion sensor element measures pitch-rate information needed by the crucial functions. Splitting the functions means qualitatively an increase in reliability and decrease in cost for obtaining just the pitch rate compared to an integrated inertial reference system. An alternative design that would take further advantage of the partitioning would use the body motion sensors for pitch rate, thereby eliminating the need for the dedicated pitch gyro type of LRU. The body motion sensor element must then satisfy the reliability requirements of the crucial pitch stability functions. Comparative life cycle costs would play a large role in evaluating the desirability of the alternative design.

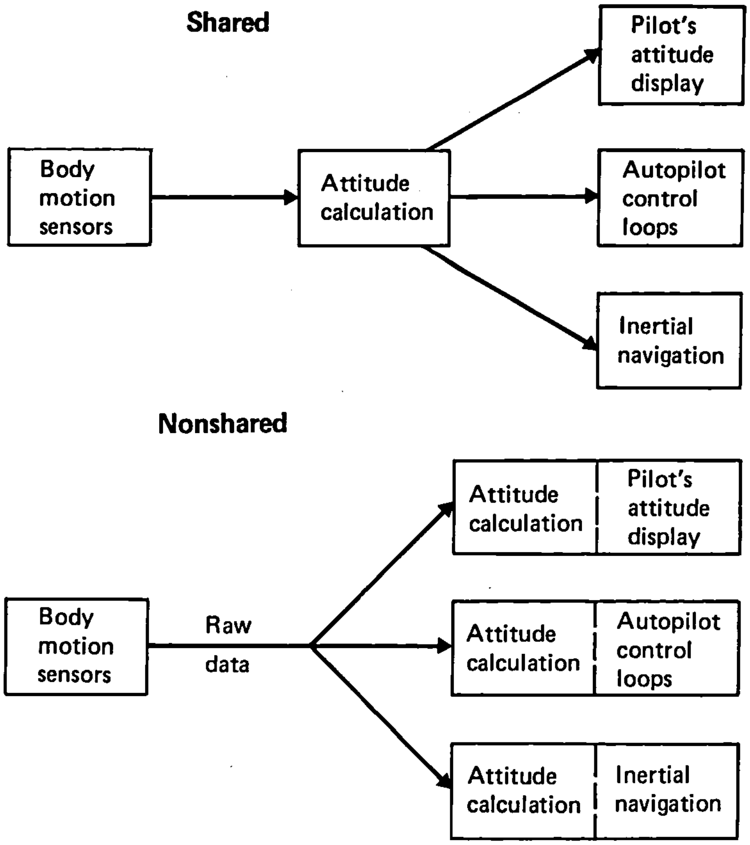


Figure 55. Data Processing Function Alternatives

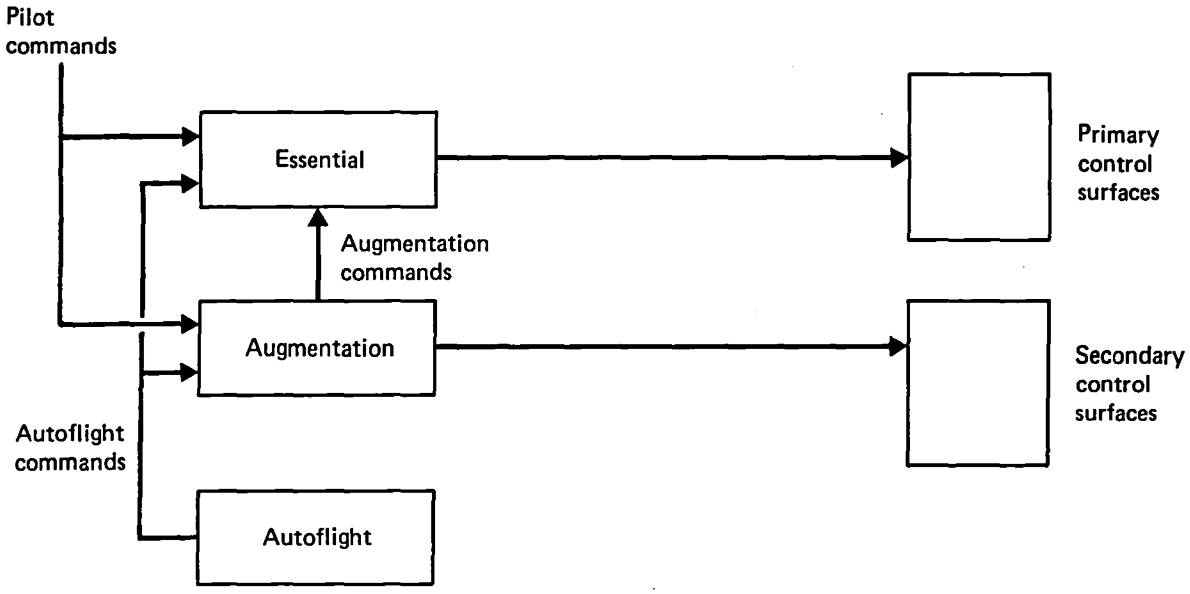
The autoflight attitude control loop is functionally and physically separated from the autoflight thrust control loop in the preliminary architecture based on criticality considerations. A study (ref 19) has shown that functionally integrated approaches can greatly simplify the autoflight system design as well as improve performance. Specifically, the natural coupling between the pitch axis and thrust axis can best be used by controlling them together rather than separately. One alternative would be to compute both controls in the same physical location. However, this would combine the less critical thrust control loop with the more critical (due to autoland) attitude control loop. This would increase the amount of functional processing and fault-tolerant overhead processing in the inner loop element and increase the related design and verification and validation effort. Another alternative would be to maintain physical separation but functionally integrate the two loops by data bus information transfer. This would require adding degraded mode behavior provisions (at least in the more critical element) to allow function survivability if the other element fails and would impact data bus information rates and overall loading. The choice of method would require further definition and comparison.

In the preliminary architecture, crucial function surface deflections are commanded by the flight essential processor group and the other surface deflections are commanded by the augmentation processor group. Therefore, all autoflight commands must be routed through the augmentation processor group. This allows some computational sharing (e.g., the wheel deflection to spoiler deflection is shared between the autoflight and manual control functions) but results in less autonomous subsystems. In this configuration, integrity of the more critical functions is preserved at the cost of having the more critical elements perform some fault checking overhead functions on the inputs from the less critical elements.

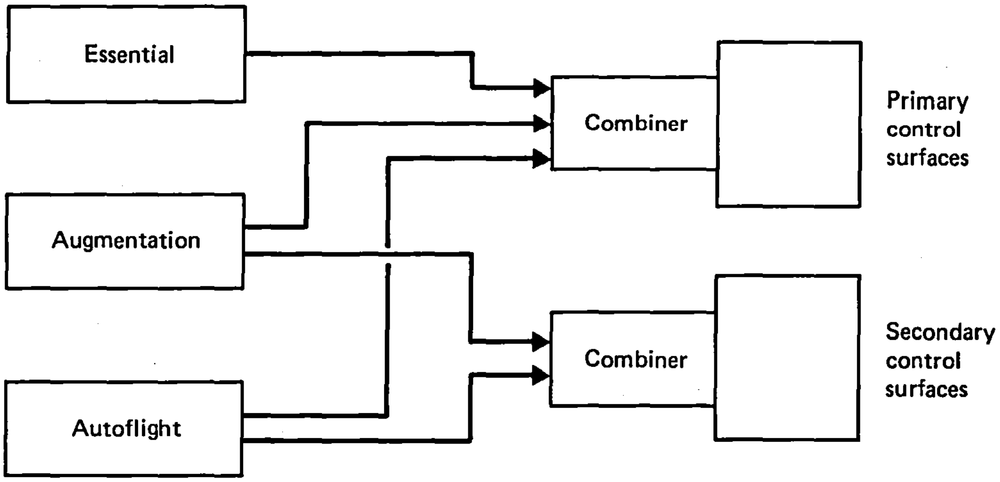
Two alternative design approaches could be taken with respect to this configuration. In the first alternative, the autoflight system inner loops would generate the equivalent of pilot control commands, which would use the same computation function as the manual flight control function to generate surface deflection commands. This would necessitate an autoflight input interface (along with fault-tolerant overhead processing) every place where the manual flight control commands are computed. This alternative would completely eliminate any need for secondary actuators for the autoflight functions and would exhibit maximum sharing of common processing functions.

The other alternative would allow the autoflight inner loops to independently calculate surface commands and directly signal the actuation interface. The command to surface deflection transfer function would have to be duplicated in the autoflight control elements and the manual control elements. This second alternative leads to a more autonomous autoflight subsystem. Both approaches would increase the amount of processing required in the more critical systems. In the first alternative, additional overhead processing would be necessary to ensure that an erroneous autoflight command would not jeopardize the pilot's capability to control the airplane. With the second alternative, a command combiner element with fault-tolerant characteristics is necessary so that autoflight-commanded surface deflections do not compromise the more critical airplane stability and control functions. Figure 56 presents a schematic of these alternatives.

In the preliminary architecture, an operative ground rule was that any element could receive data from any data bus but elements of lower criticality could not transmit on a



Common Manual-Autoflight Interface Alternative



Command Combiner Alternative

Figure 56. Surface Signal Consolidation

bus containing more critical data. This ground rule is based on characteristics of the autonomous access data bus envisioned in this study. This bus incorporates a terminal with an independent monitor element that disables the transmit function if it violates protocol. Because of this aspect, the central bus failure modes are limited to failure of the bus medium and a dual monitor and transmitter failure. Therefore, a connected element affects integrity of data transfer among other elements on the bus only by its transmit function.

Because the likelihood of a dual failure at a terminal is very low, connection of another transmitting element to a bus will have only a small decremental effect on data transfer function reliability. Therefore, it could be argued that the ground rule used in the preliminary architecture was too restrictive. Because standard terminals are used everywhere, connecting lower criticality elements to a bus does not significantly lower critical function reliability.

The navigation functions are grouped primarily with the flight management system in the preliminary architecture. This grouping has several disadvantages. First, it is obvious that the flight management system has been allocated a large amount of data processing. In addition, some of the navigation functions are more critical than the typical workload relief functions performed in the flight management system. For these reasons, an alternative would be to separate the navigation-related functions from the flight management system. In an alternative configuration, the navigation function would be performed in two elements based on criticality. One element would provide the basic inertial position data and resolved acceleration data used throughout the system. The other element would perform the other navigation functions such as combined sensor automatic navigation and automatic tuning of radio navigation aids. The second element would also contain the navigation data base. The alternative would lead to a more logical system organization but has the disadvantage of increasing the number of LRU types in the system.

7.7 SYSTEM REDUNDANCY

Page

7.7 SYSTEM REDUNDANCY

7.7.1 REDUNDANCY CONCEPTS

7.7.1.1 Basic Redundancy Needs

The integrated ACT/Control/Guidance System performs several top-level functions that are critically important to the safety of the airplane. These functions must survive the failure of any units in the system. Subsection 6.2 evaluated the top-level functions for safety criticality. In addition to safety, there are other reasons why top-level functions must be survivable on commercial aircraft. Airline spare-part inventories and logistic system costs require the airlines to stock extensive spares only at a few of their line stations. Consequently, any function required for dispatch or important for economical operation must either be very reliable or survivable enough to allow dispatch with a failed unit. Otherwise, unit failures would lead to costly flight delays or would adversely affect airline profitability on the route segment. Thus, often an incentive exists from a cost benefit point of view for an airline to specify survivability greater than that required from a safety point of view.

7.7.1.2 Redundancy Configuration Overview

Survivability is accomplished by having an alternative way to perform the top-level function. The alternative way can be a backup system using one or more different units than the primary system. Most conventional avionic systems provide the alternative way by replicating the units performing top-level functions. Use of identical redundant units has obvious life cycle cost benefits. However, a weakness of the conventional approach is that the top-level function is susceptible to common hardware failures, common software faults, or design errors in the identical units. Therefore, generic failures must be rigorously eliminated to the maximum extent possible, before operational certification, to provide survivability with this approach.

Conventional avionic systems were developed from a tradition of rigidly isolated subsystems (where feasible) dedicated to performance of certain top-level functions. This guarantees that faults in one subsystem do not affect performance of another subsystem's functions. Recent trends toward increased performance and a desire to lower initial and life cycle costs have led to much more integration in the system. To provide the same fault isolation with integration, it is necessary to carefully partition the system hardware and software so that faults do not propagate across partition interfaces.

A redundancy configuration that uses the traditional concept employs redundant units in separate channels, which are kept isolated. Each unit in the string necessary to perform the function is replicated to provide a complete redundant channel that can independently perform the function. In each isolated channel, there is only one data path through the channel. A method is required to select the channel providing the function or to combine redundant channels into a single output.

In the isolated-channel configuration, the least reliable unit dictates the number of channels necessary to meet the reliability requirement. Units with high relative reliability have the same redundancy as the less reliable units but do not significantly improve reliability of the overall system.

A configuration with cross-channel communication allows redundancy to be specified on a unit-by-unit basis. With this configuration, multiple data paths allow units to communicate with redundant units from other "channels" to perform the function. Figure 57 shows the multiple data paths. With an isolated-channel configuration, failure of a unit effectively disables all the units in its channel; while with cross-channel communication, the processes performed by a failed unit are performed by a redundant unit in another channel. However, cross-channel communication requires more complex methods to determine the units that are healthy and that should perform the top-level function. The methods or techniques for determining unit or channel status and directing participation of units or channels are discussed in Subsection 7.7.2.

7.7.2 REDUNDANCY MANAGEMENT

Redundancy management methods accomplish three major tasks: failure detection, failure identification, and system reconfiguration. Failure detection determines that there has been a failure in the system. Failure identification determines which specific unit has failed. Finally, system reconfiguration organizes the remaining good units to perform the top-level function. Redundancy management schemes range from simple methods performed by the crew to complex automatic schemes that in themselves may

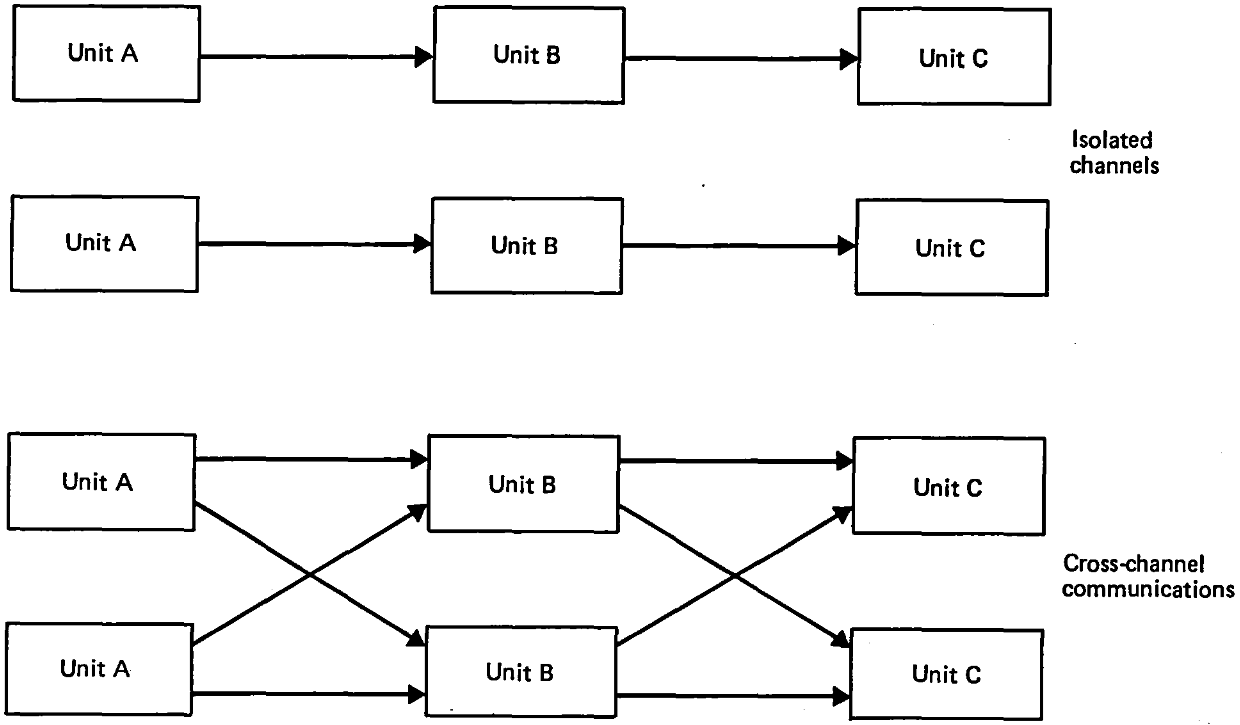


Figure 57. Isolated-Channel and Cross-Channel Communication Configurations

require more hardware and software than the functions they protect. Because of the potential for the redundancy management overhead functions to greatly burden the basic functional design, care must be taken to ensure that more complex methods are used only where they are absolutely necessary. The complexity of redundancy management should be based not only on the safety criticality of the function being performed but also on the critical time history, or rate of divergence of the system behavior when a failure occurs. For example, a function whose failure causes an immediate loss of airplane control requires a more complex redundancy management method than a function failure that is obvious to the crew members and leads to a serious consequence only after a significant period of time. Simple redundancy management using the crew members should be used where possible, because the crew can detect and identify failures by cross-checking displayed flight conditions or system status indications and then reconfigure with cockpit switches or controls. Allocating suitable redundancy management functions to the crew greatly simplifies the system design. Accordingly, this allocation must be performed in conjunction with crew roles, procedure definitions, and workload analyses to ensure compatibility of these special tasks.

Automatic redundancy management methods are typically complex, with a large overhead burden, to meet stringent performance requirements where necessary. Therefore, automatic methods present the greatest challenge to the system designer. Proper application of these methods is necessary to achieve the goal of a cost-effective design that meets requirements. The remainder of this section covers categories of these automatic methods.

7.7.2.1 Inline Monitoring

Automatic methods for detecting system failures range from inline internal hardware monitoring to comparison of the external outputs of the redundant units. With inline monitoring, the hardware elements in the system units are continually self-tested for proper behavior. Failure detection and identification occur when an element fails the test. The specific self-test design is based on the function of the hardware element being checked. A more extensive functional self-test method can be used to detect faults. In this method (stimulus and response), an input test signal pattern or sequence drives the unit or string of units. If the unit does not respond properly, it is declared faulty. Designing functional tests that can detect the significant and most probable faults is a challenging task. Functional self-test methods are currently used in preflight or preengage operations.

7.7.2.2 Output Comparison

In the external output comparison method, outputs of the redundant units are compared to determine when a failure occurs. Detection takes place when the outputs of the similar units differ by more than some threshold amount. The threshold values are selected by a compromise between false alarm probability and missed alarm probability. The most straightforward application compares outputs of identical units. A more complicated output comparison method uses a model of the system and its environment to derive a signal for comparison of outputs from one or more units.

The reasonableness checks method is a very simple model approach. A unit output value or the rate of change of the value can be compared with fixed limits that are based on whether the value or its rate of change is reasonable or physically realizable. If the output exceeds the limits, the unit is considered faulty. More extensive system models can use other sensed information to determine the best estimate of a parameter, which is compared with a unit output. Methods that detect and identify failed units by comparing derived parameter values with techniques such as Kalman filters have the advantage of requiring fewer identical units for fault identification. Of course, a tradeoff occurs between the decreased life cycle costs for a system with fewer redundant units and the increased development costs for the more complex redundancy management. More sophisticated modeling methods using advanced estimation techniques can be used to create very high performance failure detection and identification elements.

7.7.2.3 System Reconfiguration

The final redundancy management task is system reconfiguration to perform the top-level functions after a failure. Replacement of malfunctioning elements can take place on a channel basis or on a unit-by-unit basis. To reconfigure on a channel basis, only the failed channel needs to be identified; while with unit replacement, the specific unit must be identified. Some of the detection methods discussed previously have a built-in way to identify the failed unit. With channel replacement reconfiguration, redundancy management does not need to perform the failed unit identification task. Once a failure is detected, the channel is shutdown or deactivated.

For actuation functions, channel replacement can be accomplished by actuator force voting. This method uses the differential force generated between the good and bad channels to mechanically overcome or disengage the faulty channel. Redundancy management logic can also perform channel replacement by switching a bad channel off the line or switching a standby channel into control.

System redundancy is used most efficiently when individual units can be effectively replaced. The interunit selection method accomplishes this for sensor and processor units. In this method, outputs of a redundant unit are used to replace the outputs of a failed unit using cross-channel communication paths. If a unit is declared faulty, outputs from a unit in another "channel" are used to supply the downstream units in the channel with the failed unit.

As mentioned before, unit replacement requires identification of the failed unit. When output comparison methods are used for failure detection, identification is usually done with voting. Voting requires three sources of information, with the faulty source being identified by majority rule.

Signal selection is a method that continuously selects between redundant units on an individual signal basis. In this method, outputs of all redundant units are compared and one signal is passed for use by all downstream system units. This signal can be the signal from a specific unit or a composite of the signals from all of the good units. Signal selection performs failure detection for a group of units when one of the signals miscompares. Isolation is done by ignoring the faulty signal in future comparisons. The selection (or determination) of the "good" signal accomplishes any needed reconfiguration. This method is well suited to specify redundancy separately for each type of unit based on its inherent reliability.

A final reconfiguration approach that can be used with certain types of units (processing and communication) is dynamic function allocation. In this method, identical units are used throughout the system. When a unit fails, a sophisticated management function assesses which top-level functions are affected and reassigns functions as necessary among the surviving units. Through dynamic reallocation, the management function can—as far as the identical units are involved—ensure that the top-level functions are affected by failures in reverse order of their criticality. This ensures the longest possible survival of the most critical functions. This reconfiguration approach makes the most efficient possible use of the available system resources through ambitious redundancy management.

When the system does not have enough redundant units or has experienced many failures, other reconfiguration methods must be used. In these situations, loss of sensed information or actuation capability makes normal function performance impossible. The goal of reconfiguration then changes to providing degraded performance of the function. One method is to use alternative control laws. Alternative control laws are usually simpler and use substitute input parameters and/or modified gains on the unfailed actuators. Each specific failure configuration to be covered this way requires its own alternative control law.

Another method of system reconfiguration involves using modeled data to derive an estimate of the signal lost from a failed sensor. This method, which usually results in degraded performance, uses system modeling approaches mentioned earlier and employs model-derived data that can be substituted for the lost sensor output.

The level of redundancy, complexity of the redundancy management provisions, and the "layout" or configuration of the redundant units are strongly interrelated when fault tolerance performance, initial cost, and life cycle cost aspects of the system are considered.

7.7.2.4 Crucial System Redundancy Management

Figure 58 shows the redundancy management processes used by the flight essential processor group (FEPG) of the proposed system. Details of the implementation are described in the following paragraphs.

Sensor signal selection is accomplished using minimum-mean-square deviation criteria, and system elements are monitored for faults using a combination of hardware and software. Faults are primarily detected by cross-channel comparison of the output maximum-mean-square value that exceeds a specified threshold. Inline monitoring supplements cross-channel comparisons and provides fault isolation. Following a failure that leaves only two paths for a function, a disagreement between these two paths will be accomplished by comparison with a simplified mathematical model using a maximum-mean-square error criteria and thresholding.

Crucial elevator control and short-period pitch-augmented stability (PAS) functions are performed with the use of quadruple dedicated pitch sensors and triply redundant gain control signals. These signals are supplied to quadruple computers that calculate short-period PAS and also perform the fixed-gain Essential PAS computation. The four computer outputs are cross-channel interfaced into three actuator control channels and a mathematical model channel that is used for comparison. This configuration has a failure probability of less than 10^{-11}. The signal selection process is based on the minimum-mean-square error criteria; i.e., each signal is compared with the mean value of the remaining signals. The squared difference signal that provides the minimum error signal is then selected; furthermore, if the square difference signal exceeds a given threshold, then that signal is assumed to be from a faulty channel.

The function named "signal compare" is slightly different in that a specific signal is compared with the remaining signals. If that specific signal is within a predefined tolerance window, then that signal is selected. If the signal is declared faulty, another signal will be selected or, depending on the function, a shutdown signal sent.

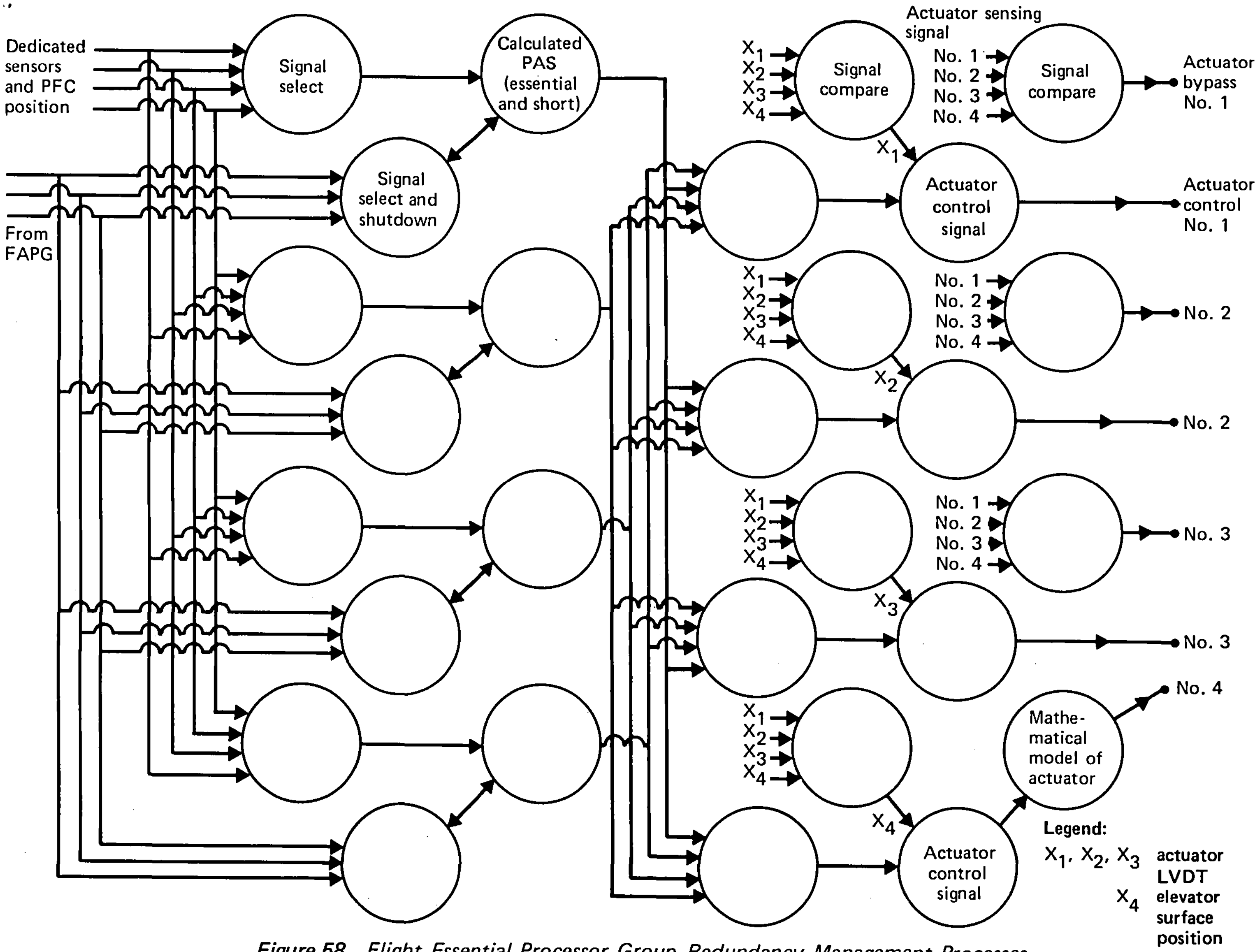


Figure 58. Flight Essential Processor Group Redundancy Management Processes

7.7.3 REDUNDANCY DETERMINATION

Subsection 6.2 describes how top-level function criticality was determined based on the impact of function loss on the safety or operation of the airplane. This criticality was used as a ground rule in grouping subfunctions together in architectural elements and as a guideline to interconnection of these elements. Once the concept architecture was defined in enough detail, the next step in the development approach was to analyze its failure behavior. In a full development effort, results of the analysis would be used to modify the concept architecture (partitioning and interconnections) iteratively to improve the resulting performance and failure behavior of the top-level functions. As mentioned previously, a strong interaction exists between the three architectural aspects of grouping, interconnection, and redundancy management. However, because the redundancy management methods have such potential for large overhead increases in the system, they are treated in a later step in this development approach.

Some comments should be made about the first fault analysis to be performed on the concept architecture. The physical architecture at this point is defined at a high level, and the emphasis is on functions rather than hardware components. Again, a purpose of this development approach is to introduce reliability concepts into the early phases of the design process. The premise is that design refinements made at this level have a high payoff potential compared to making refinements or changes later in the cycle when there is a more detailed system definition. Because this is a high-level definition of a system that will use hardware not yet developed, no experience data will be available to allow quantitative reliability analyses. Consequently, traditional reliability analysis methods will have to be slightly modified to be used in the conceptual design phase. The emphasis will have to be on qualitative rather than quantitative improvements. Quantitative methods in the early design phases must be limited to trade studies with assumed reliability numbers. Later in the development cycle, when the system hardware has been specified, traditional quantitative methods will be used. For the first look at the fault tolerance of the concept architecture, a modified fault and failure analysis was performed.

A fault and failure analysis is a procedure that evaluates the effects of potential failures on a system. What is of interest is the effect of failures on the top-level system functions. The "worst case" fault and failure analysis method was used to perform a high-level qualitative evaluation of the preliminary architecture. The method identifies all top-level functions affected by a single element worst case failure. For this study, the worst case failure considered was the total loss of all subfunctions contained in an element. Use of a few more "generic" subfunction failure types may prove to be worth the additional effort to identify additional weaknesses at this design phase.

The worst case method applied to architectural elements is similar to the criticality assessment method discussed in Subsection 6.2. A criticality is assigned to each element based on the consequences of the total loss of each element. This method will show whether the conceptual grouping of subfunctions, the numbers and types of top-level functions a particular element supports, or an element's interconnections will cause an element to be especially critical. Based on this criticality, grouping and interconnection aspects of the conceptual architecture can be changed to lower the criticality of elements, or highly critical elements can be identified for redundancy management provisions.

Appendix D presents unit criticality assessment sheets showing the results of the analysis. Figure 59 presents the criticality category results for the preliminary architecture units.

Remaining Concerns—Several of the major concerns resulting from the initial analysis of the preliminary architecture should be mentioned. Future investigation of these concerns would guide the succeeding conceptual design iterations to improve the fault behavior of the system. Central failure of any of the data buses leads to at least a large loss of system redundancy and possibly a large loss of system capability. In the preliminary architecture, elements of different criticality are connected to the same bus. The data bus interface design must prevent lower criticality element failures from causing a central bus failure. Otherwise, faults in lower criticality units could affect the higher criticality units. (A standard bus terminal design feature was assumed to make this possibility extremely remote in the development of the conceptual architecture.)

Using a set of full-authority and a set of limited-authority secondary actuators would significantly increase airplane initial and life cycle costs. It also degrades the reliability and performance of the overall system by introducing more moving parts, which are subject to wear and breakdown. Eliminating the secondary actuators will have a major impact on the architecture and will require further study.

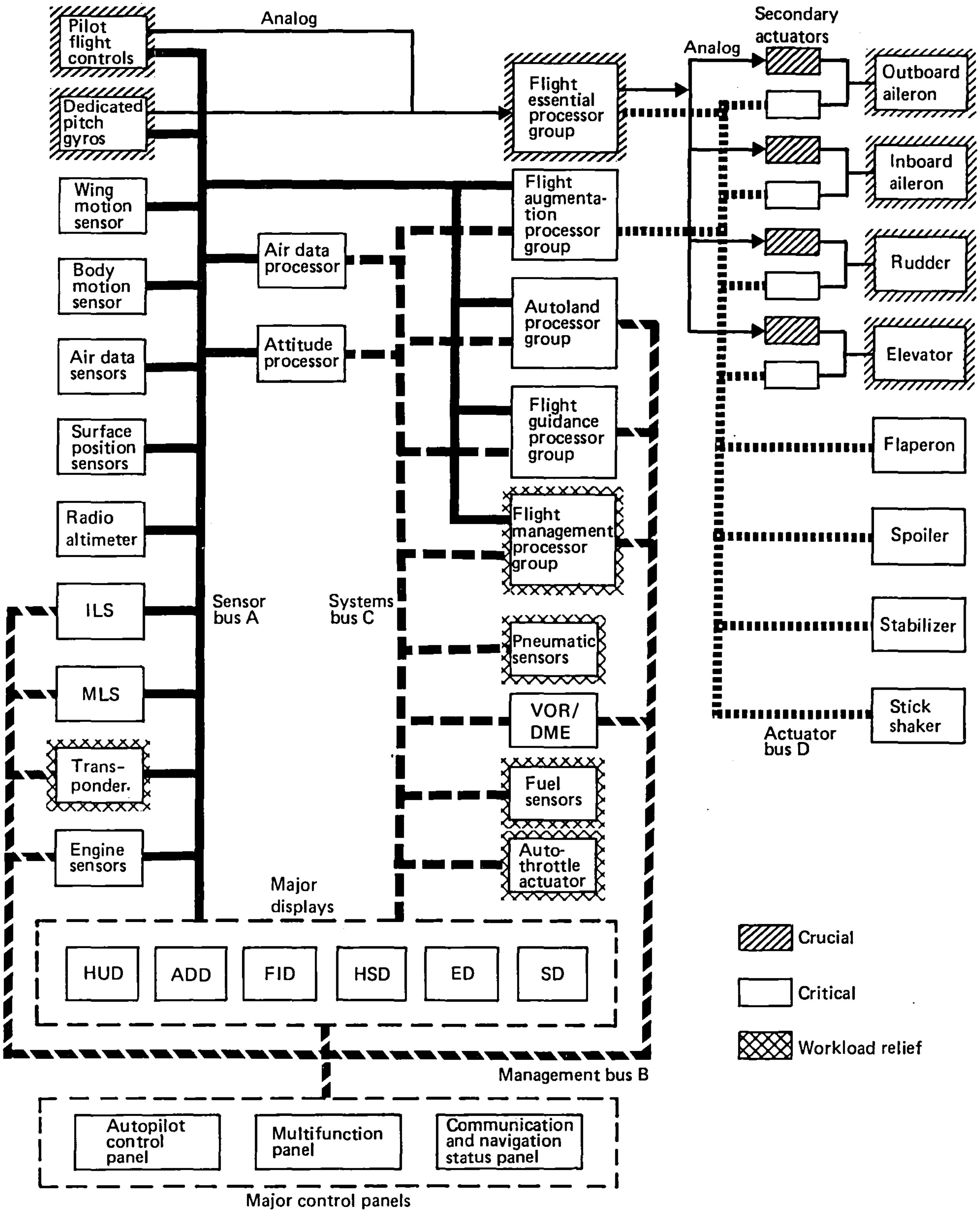


Figure 59. Criticality of Units

8.0 ACT/CONTROL/GUIDANCE SIMULATION REQUIREMENTS

8.0 ACT/CONTROL/GUIDANCE SIMULATION REQUIREMENTS

This section describes the program requirements for simulation of an integrated Active Controls Technology (ACT) Control/Guidance System with pilot in the loop. These simulation requirements provide decisionmaking planning information concerning potential implementation of the simulation. For most effective use, implementation of the simulator should commence early with long-lead items. As initial requirements for software and hardware are defined, preliminary simulation operational tests can begin. Simulator development then would continue parallel to analytic and concept definition efforts for the ACT avionics and control and display systems, which will provide effective evolution of information and total ACT control and display concepts. The final definition of implementation requirements will be produced as more comprehensive simulation test plans are completed and phased into mockup evaluations and preliminary simulations.

8.1 SIMULATION SCENARIO

A detailed preliminary scenario was constructed (app. E) to provide a baseline for derivation and planning of simulation requirements and specification of simulator design requirements. This scenario, which would be expanded and refined in future ACT studies, was structured in accordance with prime functions for each flight segment and is shown in Table 15.

For the initial development, a baseline flight scenario from Chicago to Denver was selected as representative of a composite in density and traffic variations for a modern air carrier. The basis for determining operational capability in a technologically advanced flight deck is provided by systematically identifying all tasks the airplane crew must perform. This has been done in the task analysis and is presented in detail in Appendix E, with reference to flight deck locations and functions of controls and displays listed in Appendix C.

The scenario, including flight profile and flight plan, reflects next-generation commercial transport flight operations.

Table 15. ACT Airplane Functions and Design Considerations

Segment	Takeoff	Climb
Prime functions	A. Control airplane during takeoff and transition B. Maintain communications	A. Control airplane through climbout B. Navigate to cruise course C. Maintain communications
Prime function modifiers	A. Control 1. Handling quality a. Lateral, longitudinal, and directional stability and control (1) Takeoff roll (2) Rotation (3) Transition to climb b. Control system dynamics, primary flight control (1) Augmented (2) Unaugmented 2. Crew-equipment interface a. Crew workload (1) Control requirements (2) Number of tasks (3) Displays and controls (a) Integration (b) Accessibility (4) Task allocation (5) Crew station environment (6) Operating time b. Crew accuracy (1) Display readouts and control adjustments (2) Correlating takeoff requirements with display and control response (3) Decision B. Communications 1. Communication system effectiveness 2. Communication system utility 3. Crew-equipment interface a. Equipment arrangement b. Control and display presentation c. Communication procedures	A. Control 1. Handling quality a. Lateral, longitudinal, and directional stability and control (1) Landing gear, flap, and slat retraction (2) ACT controls (3) Subsonic climb b. Control system dynamics (1) Primary flight control (a) Augmented (b) Unaugmented (2) Automatic flight control 2. Crew-equipment interface a. Crew workload (1) Number of tasks (2) Control requirements (3) Displays and controls (a) Integration (b) Accessibility (4) Crew station environment (5) Task allocation (6) Operating time b. Crew accuracy (1) Display readouts and control adjustments (2) Correlating climb requirements with display and control response (3) Decision B. Navigation system effectiveness 1. Subsystem utility 2. Crew-equipment interface a. Crew workload (1) Number of tasks (2) Task allocation and procedures (3) Operating time b. Crew station arrangement and environment 3. Equipment accuracy C. Communications 1. Communication system effectiveness 2. Communication system utility 3. Crew-equipment interface a. Equipment arrangement b. Control and display presentation c. Communication procedures
Simulator types applicable to above items	Flight control simulator (fixed base): A.1.a, A.1.b, A.2.a, A.2.b Full crew station simulator (fixed base): A.1.a, A.1.b, A.2.a, A.2.b, B.1, B.2, B.3.a, B.3.b, B.3.c Full crew station simulator (with external vision cues): A.1.a, A.1.b, A.2.b	Flight control simulator (fixed base): A.1.a, A.1.b, A.2.a, A.2.b Full crew station simulator (fixed base): A.1.a, A.1.b, A.2.a, A.2.b, B.1, B.2.a, B.2.b, C.1, C.2, C.3.a, C.3.b, C.3.c

Table 15. ACT Airplane Functions and Design Considerations (Continued)

Segment	Cruise	Descent
Prime functions	A. Control airplane during cruise B. Navigate on course C. Maintain communications D. Relieve crew fatigue	A. Control airplane through descent B. Navigate to landing C. Maintain communications
Prime function modifiers	A. Control 1. Handling quality a. Lateral, longitudinal, and directional stability and control (1) ACT controls (2) Subsonic flight b. Control system dynamics (1) Primary flight control (a) Augmented (b) Unaugmented (2) Automatic flight control 2. Crew-equipment interface a. Crew workload (1) Control requirements (2) Number of tasks (3) Displays and controls (a) Integration (b) Accessibility (4) Operating time (5) Crew station environment (6) Task allocation b. Crew accuracy (1) Display readouts and control adjustments (2) Correlating climb requirements with display and control response (3) Decision (4) Ride quality B. Navigation system effectiveness 1. Subsystem utility 2. Crew-equipment interface a. Crew workload (1) Number of tasks (2) Operating time b. Crew station arrangement and environment 3. Equipment accuracy C. Communications 1. Communication system effectiveness 2. Communication system utility 3. Crew-equipment interface a. Equipment arrangement b. Control and display presentation c. Communication procedures D. Crew fatigue 1. Ride quality 2. Crew station arrangement and environment a. Rest b. Food c. Sanitation d. Exercise	A. Control 1. Handling quality a. Lateral, longitudinal, and directional stability and control (1) Low-speed dynamics (2) Gear, flaps, and slat extension (3) ACT controls b. Control system dynamics (1) Primary flight control system (2) Automatic flight control system 2. Crew-equipment interface a. Crew workload (1) Control requirements (2) Number of tasks (3) Displays and controls (a) Integration (b) Accessibility (4) Operating time (5) Crew station environment (6) Task allocation b. Crew accuracy (1) Display readouts and control adjustments (2) Correlating descent requirements with display and control response actions B. Navigation system effectiveness 1. Subsystem utility 2. Crew-equipment interface a. Crew workload (1) Number of tasks (2) Operating time (3) Crew station arrangement and environment (4) Task allocation and procedures b. Crew accuracy (1) Display and control operation (2) Decisions 3. Equipment accuracy C. Communications 1. Communication system effectiveness 2. Communication system utility 3. Crew-equipment interface a. Equipment arrangement b. Control and display presentation c. Crew-equipment interface (1) Equipment arrangement (2) Control and display presentation (3) Communication procedures
Simulator types applicable to above items	Flight control simulator (fixed base): A.1.a, A.1.b, A.2.a, A.2.b Full crew station simulator (fixed base): A.1.a, A.1.b, A.2.a, A.2.b, B.1, B.2.a, B.2.b, C.1, C.2, C.3.a, C.3.b, C.3.c, D.2 Full crew station simulator (with motion): A.1.a, A.1.b, A.2.a, A.2.b, B.2.a, C.3, D.1	Flight control simulator (fixed base): A.1.a, A.1.b, A.2.a, A.2.b Full crew station simulator (fixed base): A.1.a, A.1.b, A.2.a, A.2.b, B.1, B.2.a, B.2.b, C.1, C.2, C.3.a, C.3.b, C.3.c

Table 15. *ACT Airplane Functions and Design Considerations (Concluded)*

Segment	Landing	
Prime functions	A. Control airplane through approach and landing B. Navigate to runway C. Maintain communications	
Prime function modifiers	A. Control 1. Handling quality a. Lateral, longitudinal, and directional stability and control (1) Low-speed dynamics (2) Landing flare b. Control system dynamics (1) Primary flight control (2) Automatic landing control 2. Crew-equipment interface a. Crew workload (1) Control requirements (2) Number of tasks (3) Displays and controls (a) Integration (b) Accessibility (4) Operating time (5) Crew station environment (6) Task allocation b. Crew accuracy (1) Display readouts and control adjustments (2) Correlating landing requirements with display and control response actions (3) Decision B. Navigation system effectiveness 1. Subsystem utility 2. Crew-equipment interface a. Crew workload (1) Number of tasks (2) Operating time (3) Crew station arrangement and environment (4) Task allocation and procedures b. Crew accuracy (1) Display and control operation (2) Decisions (3) Ride quality 3. Equipment accuracy C. Communications 1. Communication system effectiveness 2. Communication system utility 3. Crew-equipment interface a. Equipment arrangement b. Control and display presentation c. Communication procedures	
Simulator types applicable to above items	Flight control simulator (fixed base): A.1.a, A.1.b, A.2.a, A.2.b Full crew station simulator (fixed base): A.1.a, A.1.b, A.2.a, A.2.b, B.1, B.2.a, B.2.b, C.1, C.2, C.3.a, C.3.b, C.3.c Full crew station simulator (with motion and external vision): A.1.a, A.1.b, A.2.a, A.2,b, A.1.b	

To completely evaluate the man-system interface, especially as affected by ACT function failures and marginal handling qualities, such failures or abnormal operation of representative systems and subsystems must be simulated during appropriate flight phases. For maximum simulation validity, these abnormal operations must be integrated into normal operations in a realistic environment such that the crew is tested in response patterns and priorities of duties. This yields accurate data about handling qualities, control and display effectiveness, and the simulation methods themselves. Table 16 lists typical non-ACT abnormal procedures that might apply to any 1990s airplane. These simulated failure capabilities will also be available in the ACT simulator, permitting a full appraisal of overall workload capability for worst case ACT airplane operations.

Emergency procedures are similar to abnormal procedures in that neither occurs frequently in real operations, but in a developmental simulator the capability must exist to thoroughly explore such man-system interface effects and response capability and reserve. The primary difference between abnormal and emergency procedures is that abnormal procedures seldom affect the specific flight profile that has been planned.

Emergency procedures, however, quite often will totally and drastically change the flight profile (e.g., rapid decompression). In a matter of minutes, the available range of the airplane may not equal the range to the planned destination. Some emergency procedures can tax the crew to the maximum extent because of simultaneous critical-action control requirements, rapid system and subsystem operation or modification, decisionmaking, communications, and navigation. In this environment, a flaw in the man-system interface may appear sooner than anywhere else. Accordingly, it is essential that such problems be detected and resolved in the benign environment of a simulator. Table 17 lists typical emergency procedures that might apply to the ACT-configured airplane. These capabilities should also be available in the simulator.

Table 16. Typical Non-ACT Abnormal Procedures

	Abnormal procedure
Engine	Engine start in flight Engine failure and shutdown Engine shutdown maintenance information One engine inoperative landing and missed approach Inadvertent thrust reversal in flight Reverse thrust, reverse unlock, or reverse valve open Engine oil pressure low Engine oil strainer clog
Fuel dumping	Fuel dumping
Electrical	Generator bus failure dc loadmeter zero Generator fail Generator off Constant-speed-drive oil temperature high Constant-speed-drive oil pressure low
Hydraulics	Hydraulic temperature high Hydraulic temperature gage high Hydraulic pump low pressure Hydraulic pressure gage low Hydraulic quantity loss
Flight controls	Landing with normal flaps and abnormal slats Landing with normal slats and abnormal flaps No-flap/no-slat landing Stabilizer inoperative landing
Landing gear	Antiskid fail Gear unsafe with gear handle down Gear unsafe with gear handle up Gear handle will not go to up position Gear handle will not go to down position
Air-conditioning smoke	Air-conditioning and pneumatic supply smoke Cockpit smoke removal—unpressurized Ram air ventilation system operation
Anti-ice cockpit window	Engine or wing—anti-ice valve inoperative Pitot heat inoperative Cockpit window failure Windshield anti-ice inoperative
Ditching	Ditching and ditching evacuation

Table 17. Typical ACT Airplane Emergency Procedure Conditions

Emergency procedure condition
Short-period PAS failure
Rapid decompression
Engine fire or severe damage
APU fire
All engines flame out
Loss of all generators
Electrical smoke of unknown origin
Pneumatic temperature failure

8.2 GENERAL SIMULATION REQUIREMENTS

The simulation requirements discussed in this subsection are presented in terms of tasks and task objectives, simulation design and evaluation tools used, and preliminary schedule and cost estimates. The importance of relating the simulation program to the airplane development program is to be considered implicit throughout.

Figure 60 shows a block diagram of all flight simulations to be considered. The figure applies throughout the range of simulation sophistication, as the actual mechanization of simulation can vary from a simple, single-task, fixed-base cockpit-computer combination to a complex, multitask experiment that could include such sophisticated capabilities as moving-base and external vision cues. For the present discussion, it will cover simulation from early handling qualities efforts through flight support evaluations for an ACT airplane.

Detailed planning of expected handling qualities and control and display refinements exceeded the scope of the current effort. A more explicit definition of design questions is needed as part of planning simulation goals and simulation design tools. An extended review of the simulation implications of all systems is only part of the effort required to produce an overall test program plan that consists of a series of individual simulation test plans.

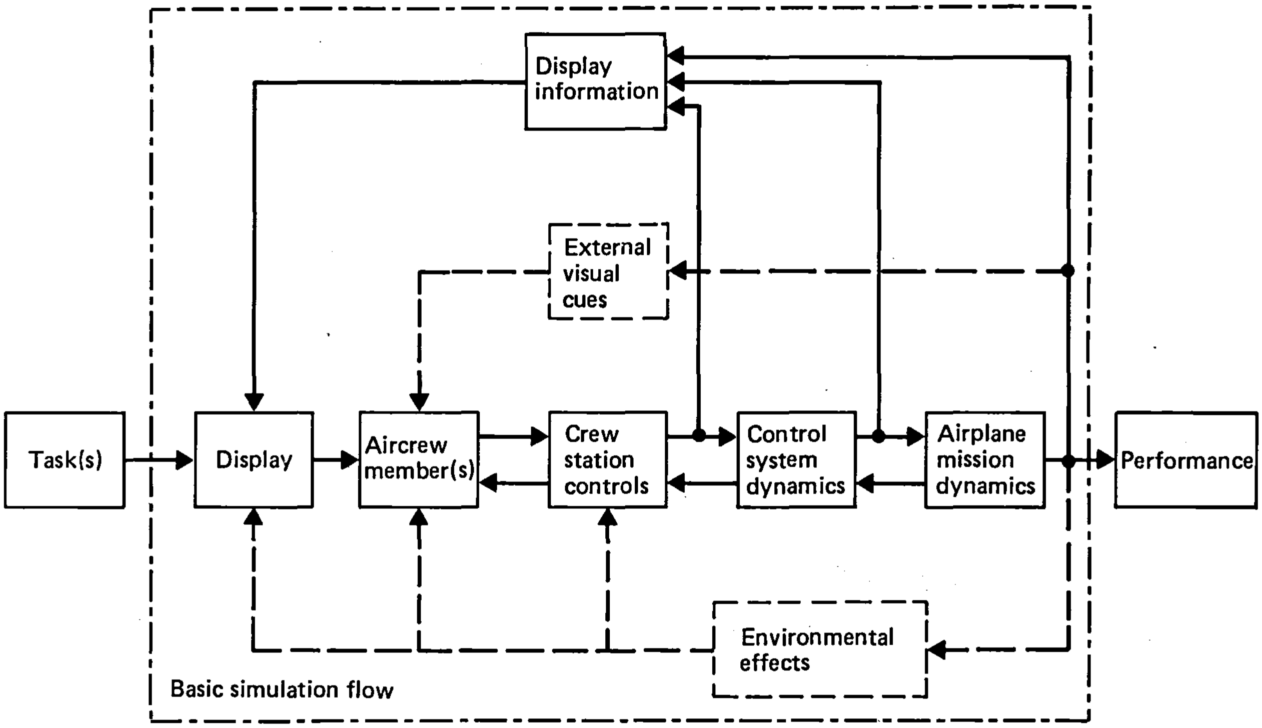


Figure 60. Flight Simulation Diagram

The present study provides a general scope of requirements involved in the simulation program that is deemed necessary for all system development phases. The requirements relate to the time period from the end of the present study through airplane test. A more extensive definition of the factors significant to such a program is needed in the next study phase.

8.2.1 ACT AVIONICS AND CREW SYSTEM SIMULATION TASKS

Under a separate task, but concurrent with work on this IAAC task, a piloted simulation study of the Boeing 757 airplane was conducted at aft center-of-gravity (cg) locations with an ACT system. The study was done to show the feasibility of providing good handling qualities at extremely aft cg locations within the operational and design flight envelopes. The results of this study are documented in Reference 20.

Evaluations were made of the unaugmented airplane, the airplane with an Essential Pitch-Augmented Stability (PAS) System, and the airplane with a full-capability Primary PAS System. Acceptable (with improvements warranted) pilot ratings were attained aft to about 57% mean aerodynamic chord (MAC) or 6% aft of the neutral point for unaugmented landing approach. For Mach = 0.80 unaugmented cruise, acceptable ratings (with improvement warranted) were attained to 47% MAC or 5% forward of the maneuver point. The augmented airplane model provided handling qualities close to, or within, a good (no improvements necessary) rating at all tested cg locations for both the Essential and Primary PAS Systems. Analyses of the test conditions, applied to existing handling qualities criteria, agreed well with the unaugmented airplane ratings. However, modifications of some of the criteria are suggested by the augmented airplane ratings.

The simulations of the present phase (table 18) would require a simulation study of significantly greater scope during actual flight readiness testing. Demonstration of flight readiness of detailed augmentation system designs, ensuring manageable manual reversion for all flight and control and display workload conditions, will require simulation testing of ACT flight test hardware, flight-standard processors, and associated control laws.

The scope of a "first cut" simulation would be similar to that of the earlier (ref 20) piloted simulation, extending earlier information to correlate with design differences. However,

Table 18. Representative Handling Qualities Simulations

757 Simulation Test Flight Conditions

Condition	Weight		Gear	Flight path angle, γ	V_e		Mach No.	Altitude		Neutral point	Maneuver point
	kg	(lb)		deg	m/s	(KEAS)		m	(ft)	Percent MAC	Percent MAC
Landing conditions	89 813	(198 000)	Up	-3.0	69	(134)		305	(1 000)	48	65
	89 813	(198 000)*	Down	-3.0	69	(134)		305	(1 000)	50.5	62
	89 813	(198 000)	Down	0	69	(134)		305	(1 000)	49	62
	73 483	(162 000)	Down	-3.0	63	(123)		305	(1 000)	51	71
Cruise conditions	86 184	(190 000)	Up	0			0.80	10 668	(35 000)	41	52
	83 462	(184 000)*	Up	0			0.80	10 668	(35 000)	36	52
	83 462	(184 000)	Up	0			0.82	10 668	(35 000)	31	48
	83 462	(184 000)	Up	0			0.84	10 668	(35 000)	33	47
	83 462	(184 000)	Up	0			0.80	11 887	(39 000)	42	51
	74 844	(165 000)	Up	0			0.82	11 887	(39 000)	40	47
	83 462	(184 000)	Up	0			0.82	12 802	(42 000)	–	46
	83 462	(184 000)	Up	0			0.86	8 230	(27 000)	–	50
	83 462	(184 000)	Up	-4.9			0.91	7 620	(25 000)	–	58
	83 462	(184 000)	Up	0			0.63	3 050	(10 000)	39	55
	83 462	(184 000)	Up	0	100	(195)		7 620	(25 000)	44	51
Climb condition (maximum power)	74 844	(165 000)	Up	10.0	144	(280)		3 050	(10 000)	31	57

*Principal simulation test conditions.

Pilot Simulation Maneuvers

Low-speed maneuvers

Approach and landing or go-around

Initial conditions
SX = -6096m (-20 000 ft), SY = 305m (1000 ft)
Alt = 152m (500 ft), $\gamma = 0$ deg, $V_e = 1.3V_S + 10.3$ m/s (20 kn)
Gear up, flaps = 20 deg

Flight profile

- 1.5 dot below glide slope—gear down[a]
- 1.0 dot below glide slope—flaps 30 deg, reduce to $1.3V_S$
- Glide slope capture
- Approach on instruments at $1.3V_S$
- "Breakout" at 30.5m (100 ft)
- Land
  or
- Go-around at 15.2m (50 ft), full power, flaps = 20 deg
- Gear up at positive rate of climb

With and without moderate turbulence and 10.3-m/s (20-kn) crosswind at 12.2m (40 ft)

$(\sigma_u, \sigma_v, \sigma_w)$ = (1.52, 1.52, 0.76) (m/s) (rms)
((5.0, 5.0, 2.5) (ft/s) (rms)

Reference speeds

74 844 kg (165 000 lb) $1.3V_S$ = 63 m/s (123 kn)
89 813 kg (198 000 lb) $1.3V_S$ = 69 m/s (134 kn)

High-speed maneuvers[b]

Still air

- Roller coaster $\Delta\ddot{z}$ = ±0.5g
- Altitude change Δalt = ±91.4m (300 ft)
- Speed change Δu = ±7.7 m/s (15 kn)
- Roll in/out $\Delta\phi$ = 30 deg, $\Delta\psi$ = 15 deg

Turbulence (moderate)

- Altitude change Δalt = ±91.4m (300 ft)
- Roll in/out $\Delta\phi$ = 30 deg, $\Delta\psi$ = 15 deg

[a] 1.0 dot indicates approximately 0.35-deg deviation from glide slope.
[b] Initial conditions within the flaps-up flight envelope boundaries are applicable.

Source: Boeing (ref 20).

beyond such a first-cut simulation effort, all of the failure modes will have to be analyzed and evaluated. The detailed simulation would include exhaustive evaluation of ACT system functions and failures superimposed on the system and crew workloads of normal flight phases.

Simulation of a 1990s ACT airplane flight deck, the controls and displays of which are interactive with an integrated ACT avionic system, will encompass the following task groups:

Group 1—System architecture selection and simulation implementation engineering

Group 2—System failure modes and effects analysis and selection of failure modes to be simulated

Group 3—Simulation scenario(s) refinement with superposition of selected ACT failures

Group 4—Simulation cab layout design, accommodating expected ACT failure mode influence on crew task priorities

Group 5—Iterative simulation experiments for data collection

Group 6—Data analysis and conclusions abstraction

Task Objectives—The preceding task groups will provide determinations in the following three major investigative areas:

- Handling qualities will require extensive iterative simulation. While Reference 20 provides data for one tightly bounded, relaxed-stability experiment, it remains to refine controllability of an ACT airplane for normal operations and to resolve handling qualities characteristics for all degraded modes. A variety of degraded modes is possible, each with potentially more significant impact on controllability than experienced with more traditional airplanes.

- The pilot's control and display interface for primary flight control will require dedicated attention and may need some significant design modifications tailored to handling qualities evolution. Combinational failure modes could result in a marginally unstable airplane in an environment that severely restricts the pilot's options for correction of the condition. Skill and workload demands on the crew will change with variations in handling qualities, and special display formatting features are expected to be necessary to ensure and enhance pilot awareness, comprehension, and effective control. Past experience with such features as the electronic horizontal situation indicator (EHSI) "trend vector" has shown that the pilot's control capability and responsiveness to new situations can be improved by displaying status, trends, rates, and overall predictor information.
- The handling qualities control and display workload must be demonstrated to be manageable in context with total system management and control. As the full range of failure modes affecting manual flight control capabilities is resolved, a new, ACT-related workload baseline will emerge for the primary flight control task. Design questions may arise regarding crew workload reserve for other key flight and system management duties, requiring extensive simulation to ensure effective total control and display system formatting for monitoring and controlling the other airplane systems. Accordingly, periodic appraisals of the total flight deck workload would be necessary as part of the simulation evaluations, leading to total flight deck simulation.

The data developed during work on the preceding three major interest areas should produce answers and conclusions regarding:

- Handling qualities versus envelope boundaries for all flight phases
- Effects on handling qualities of the various control laws applied
- Effects on both handling qualities and crew workload of the selected modes of system failures imposed
- Design modifications or implications for the interface between the flight deck and crew systems resulting from the preceding three items
- Design modifications or implications that all of the preceding impose on the simulated ACT avionics and crew system integrated system

8.2.2 ACT AVIONICS AND CREW SYSTEM ELEMENTS AND FUNCTIONS SIMULATED

The choice of system elements requiring simulation as equipment items—as contrasted with functions to be simulated—is a subtask of a future phase of work, falling within the Group 1 and Group 4 tasks described in Subsection 8.2.1. In general, however, because it is finally the crew that is being tested in the measurement of airplane handling qualities and workload manageability, the system elements that provide the crew its interface have unquestioned influence on test results. The benefits or drawbacks of a multifunction display panel with keyboard to crew task performance cannot be extrapolated from simulating such a device with electromechanical displays and switch sets, for example. For these reasons, flight deck elements of the system require close physical and manipulative simulation.

In general, other system elements may be simulated in terms of their interactive functional effects at the flight deck interface. Function generation or simulation is the design task rather than the element emulation.

Flight Deck Simulation—The ACT avionics systems required to be simulated at the flight deck interface cover three prime areas: ACT-unique functions, control and display integration, and new-technology displays. Each of these areas requires careful simulation for development, integration, workload analysis, and degraded mode analysis.

The ACT-unique functions are grouped into the following types of functions:

- Control Functions—The control functions are minimal, considering the inherent transparency of the ACT systems. The only immediately obvious controls will be the emergency disconnect switches located on the overhead flight control panel. These switches will be guarded switches capable of being reset after a disconnect. There will be one switch for each of the individual ACT functions (speed PAS, lateral/directional-augmented stability, wing-load alleviation, maneuver-load control, gust-load alleviation, and angle-of-attack limiting). The only other controls consist of test initiation switches used to start the mechanical and electrical test sequences, respectively. Rather than using dedicated switches, these functions would be controlled through the multifunction keyboard as part of the preflight operational sequence.

- System Status Functions—ACT system status is monitored directly through the systems display and crew alerting systems. The systems display will show ACT system status only upon pilot request and any present system faults and list flight restrictions as applicable. The crew alerting system will provide fault annunciation on a real-time basis. The level of alert will be commensurate with the severity of the fault as it impacts the entire ACT system.

- Maintenance Functions—The ACT maintenance functions recognize and store information on three levels of faults:

    - Faults that have no effect upon airplane dispatchability
    - Faults that allow dispatch but with some restriction to the flight plan
    - Faults that prevent dispatch

These functions will be included in the crew alerting system, which allows storage of all system faults. The crew alerting system information could also be data linked to ground operations through the ARINC communication addressing and reporting system (ACARS).

Control and display integration is a most important area, as reversion to manual control of the ACT airplane could require improved predictor displays and special-purpose formatting and display dynamics. This area perhaps requires the most simulation, commencing with earlier handling qualities effort to ensure overall compatibility of pilot control and display characteristics with airplane response. For the ACT airplane, this integration involves several new flight deck controls and displays that have been evolving and that are expected to enhance pilot operation and control. The following controls and displays are now sufficiently mature and ready to start the application-refinement process to enhance flight deck control of operations and to aid in workload control:

- Centralized crew alerting system
- Multifunction control and display unit
- Engine and system monitor displays
- Integrated communication and navigation panel
- Electronic secondary displays

New-technology displays to support control and display integration include expanded use of color cathode-ray tubes (CRT), introduction of flat panel displays (i.e., light-emitting diode and thin-film electroluminescence), and development of holographic head-up display projection. Color CRT use in the cockpit is becoming commonplace; therefore, much analytical data and experience will be available to the designers and system integrators, reducing simulator development and testing hours. Flat panels, being new to the cockpit, will require greater system development and testing. Similarly, the head-up display will require more hardware refinement. Head-up display software and associated drive algorithms are presently being developed, tested, and refined jointly by industry, FAA, and NASA. This work will valuable to the simulation system development.

Some of these concepts are already being developed, such as the centralized caution, warning, and advisory system on the Boeing 757/767 airplanes and the radio management system under development for the Boeing 737-300 airplane. Significant refinements (e.g., dynamics and formatting) are feasible and desirable for the ACT airplane to ensure that the flightcrew has basic backup flight control capability for all normal and failure modes. In addition, new system management concepts are expected to be necessary to alleviate crew workload during manual reversion. New questions to be addressed in simulation integration will extend earlier control and display integration concepts and also deal with interaction of the multifunction control and display unit and the engine and system monitor displays.

It remains to extend the present definition of simulation requirements into a specific test planning activity. Such effort is beyond the scope of the present effort but is recommended for more efficient evolution of the simulation program. The detailed test plans will be based on the scenario and function-action-information requirements of Appendix E. The planning activity would ensure outlining not only representative normal flight mission requirements but also incorporating (in context) various degraded modes that might occur. Initial evolution of the scenario will be modified and extended significantly as feedback and updating continue. Simulation planning herein is based on the present definition phase for the scenario and is subject to updating.

8.3 RECOMMENDED SIMULATION MECHANIZATION

The recommended simulation mechanization, details of which are given in Appendix F, closely follows design testing and handling qualities verification proven valid in similar Boeing programs.

The simulation would require a general-purpose (fixed base) cab, selected support use of a motion simulator cab, multiprocessor computer system availability, cab device development effort, and scenario-unique software development in addition to real-time simulations and data analysis tasks.

The engineering budget estimate for such a mechanization is approximately $3 million for pretest costs of labor, hardware, and cab devices and between 30 and 40 man-years of simulation team effort in software design, simulation testing, and data analysis.

9.0 CONCLUDING REMARKS AND RECOMMENDATIONS

In this project, stipulation of a 1990s ACT-configured airplane provided a sufficiently long look into the future to realistically accommodate an expected evolution of design methodology, as applied to commercial air transports. A top-down avionic system design and development approach is a departure from the methods traditionally used by commercial airframe manufacturers; i.e., aerodynamics, structures, and propulsion have always dominated the engineering process, with individual avionic systems being added randomly where needed on the airplane because of the services that they provide. But the avionic systems are now beginning to play an important role in fuel economy, airplane safety (e.g., collision avoidance), flight comfort, and flight operations. Moreover, digital electronics and all-electric actuators may eventually replace many hydraulic systems, providing weight and cost savings and improved maintainability.

This ACT/Control/Guidance System study provided the first opportunity to apply a systematic top-down approach to avionic system design, generally unconstrained by preconceived notions of what the system architecture should be. Discussions with 757/767 program people also benefited this ACT study considerably; because the 757/767 airplanes are the first "all digital" commercial transports, many valuable lessons have been learned that can be applied to the next-generation system.

Analysis of the preliminary system architecture led to the conclusion that—as a consequence of elements of various criticalities being connected to a common bus—the data bus interface design must prevent lower criticality element failures from causing a central bus failure. Thus, a standard bus terminal design feature was assumed to make such a central bus failure possibility extremely remote. System reliability analyses for such an architecture would be heavily dependent on the ability to implement such a design feature.

The system architecture alternatives examined included—among other aspects—backup systems providing degraded performance in lieu of the redundant, full-performance system; various ways of combining (or separating) processing functions; and such specifics as a choice between primary or secondary actuators and split control surfaces. Complete evaluation of some of these alternatives will require cost, weight, reliability, and maintainability trade analyses. For others, there may even be a need for additional technology development before valid decisions can be made.

Other principal conclusions and recommendations reached during the course of this work are:

- A structured approach to hardware and software development will be very beneficial and perhaps essential to any future avionic system design.

- The ACT/Control/Guidance System imposes no unusual constraints on flight operations and no additional functional capability for air traffic control (ATC) clearances.

- Manpower and schedule constraints dictated that the flight deck functions be determined separately from but parallel to the rest of the avionics functions. Additional work will be required to achieve consistent integration of the two portions of the system.

- The assumptions and constraints governing the system design proved to be satisfactory throughout this study.

- No significant changes are foreseen for the required functions, the logical groupings, or the high-level data flow; however, all systems should have data flow developed to a degree at least equivalent to that shown for the "control and structural relief" group.

- Functions such as electrical power should be addressed in any future work.

- Details of the preliminary architecture are still at a fairly high level; it is expected that some of the architectural concepts (even at this high level) may change when the next lower level of detail is developed. During the study, it was found that two to four iterations were necessary at adjacent levels of design detail.

- Potentially attractive system architecture alternatives have been identified.

- A thorough analysis of system performance, including data bus loading, redundancy, software overhead requirements, growth capability, etc., must be performed before the next lower level of design detail is developed.

- User (airline) reaction to the new, integrated system concepts should be determined.

- The new system concepts should be examined and distributed by Aeronautical Radio Incorporated (ARINC) to ensure timely suggestions and consensus from the entire aviation community.

- Projections of hardware reliability must be developed.

- System software development and maintenance burden implications were addressed only in the ground rules and constraints affecting system architecture (i.e., there would be extensive use of common software functions, etc.). It is recommended that cost and reliability tradeoffs specific to avionic system structuring be studied further.

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16. Abstract

This report documents the ACT/Control/Guidance System Task of the Integrated Application of Active Controls (IAAC) Technology Project within the NASA Energy Efficient Transport Program. The air traffic environment of navigation and air traffic control systems and procedures were extrapolated to the 1990s era for conclusions bearing on ACT airplane consequences of avionic system elements and operating procedures. A top-down approach to listing flight functions to be performed by systems and crew of an ACT-configured airplane of the 1990s, together with a determination of function criticalities to safety of flight, formed the basis of candidate integrated ACT/Control/Guidance System architecture.

In addition to the conventional control and navigation functions, the system mechanized five active control functions: pitch-augmented stability, angle-of-attack limiting, lateral/directional-augmented stability, gust-load alleviation, and maneuver-load control. The scope and requirements of a program for simulating the integrated ACT avionics and flight deck system, with pilot in the loop, were defined in terms of simulation scenario, system and crew interface elements to be simulated, and the recommended mechanization. Particular attention was given to the requirement to evaluate relationships between system design and crew roles and procedures.

17. Key Words (Suggested by Author(s))
Energy Efficient Transport, Active Controls Technology, ACT/Control/Guidance System, Pitch-Augmented Stability (Essential), Wing-Load Alleviation, Angle-of-Attack Limiting, Digital Autonomous Terminal Access Communication, Digital Data Bus

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