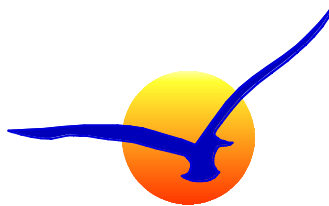04250-02

Multi-Modal Digital Avionics
for
Commercial Applications

Mark Peters

John Sorensen

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Submitted by:

Seagull Technology, Inc.

1700 Dell Avenue

Campbell, CA 95008-6902

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Acronyms

1. Introduction

NASA Glenn Research Center (GRC) plans to develop and demonstrate the flexible capabilities of multi-function, multi-mode digital avionics (MMDA) for civil aviation applications including communications, navigation and surveillance functions. This report provides a summary, review, and assessment of relevant commercial aircraft avionics capabilities and technologies toward developing MMDA.

1.1   Background

The advent of practical digital computers has changed radically many facets of life in the relatively short period of 30 years. Tasks that used to be arduous and manual in nature can now be performed effortlessly and often automatically. One of the most apparent examples of this transformation has occurred in the world of aviation. The modern air transport's flight deck is equipped with colorful, sharp displays and screens that bear little resemblance to the round dials and gauges of past aircraft. A pilot of 30 yrs ago would recognize few items beyond the control yokes in the modern cockpit.

In aviation, the first move towards digital automation occurred when Honeywell and Smiths Industries introduced the Flight Management Computer (FMC) in the 1970's. The FMC was designed to help automate the task of navigation and to manage the trajectory of the aircraft. Additionally, the FMC managed fuel consumption and other systems. The FMC was the first example of a multi-modal digital avionics device installed on an aircraft. Since the FMC managed many different aspects of the aircraft's flight, it also soon became the center of a network of avionics systems that used to function independently.

The need for the distribution of large amounts of information between avionics systems soon made old analog wires impractical, and digital data buses such as the ARINC 429 data bus were developed in the late 1970s. These buses moved the information of many hundreds of analog wires, further creating an integrated network of systems.

In the early to mid-1980s, it was becoming apparent that an integrated digital cockpit could greatly enhance the safety and reliability of the flight deck while reducing pilot workload. Advances in computer display technology also started to make electronic cathode ray tube (CRT) displays practical. Older text-only displays yielded to newer graphical displays, and analog mechanical flight instruments started to be replaced by digital components.

In 1990, McDonnell Douglas introduced the MD-11 flight deck which was the first all digital / all glass cockpit. The MD-11 represented the culmination of flight deck integration concepts and ideas conceived in the 1980s.

The MD-11, while all digital, was still an aircraft equipped with many single purpose digital components networked together. In the 1990s, the avionics trends shifted towards more centralized, multi-modal architectures where one component would host many functions. This is still the dominant thinking behind avionics design.

 Today modern avionics perform a host of different functions. The modern FMS is truly multi-modal as it incorporates capabilities for navigation/communication radio, flight planning, vertical

and lateral guidance, data link for flight plan updates and weather information, and air data /attitude, in addition to the original performance optimization features [H02]. Both Smiths Industries Aerospace and Honeywell are incorporating required time of arrival (RTA) and required navigation performance (RNP) features in their new FMS designs [S04].

Another example of multi-modal avionics for civil transports is the Engine Indication and Crew Alerting System (EICAS). The EICAS is designed to provide all engine instrumentation output and crew annunciations in an integrated format. The information supplied includes display of torque, interstage turbine temperature, high and low pressure gas generator RPM, fuel flow, oil temperature and pressure. As part of the EICAS, graphical depiction of selected aircraft systems can be displayed. Such systems as electrical, hydraulic, deicing, environmental, and control surface position can be represented [Ca01].

Communication systems have also become multi-modal. The Future Air Navigation System (FANS) is the next generation concept for more efficient communication, navigation, surveillance and air traffic management (CNS/ATM), based heavily on satellite technology.

Multi-modal digital avionics systems not only help to improve safety and optimize the flight route, but they improve communications between the aircraft and the ground. The improved flight deck layout appreciably lessens the crew's workload [H02]. We discuss the many aspects of MMDA for civil transport and general aviation in this report.

1.2   Document Focus

Our investigation has focused on six key areas. These are:

a. Description of the multiple functions and integrated modes within the MMDA design for today's commercial and business class aircraft;
b. Sequential or simultaneous operations or functions and modes;
c. Approach used for compliance with certification requirements;
d. Applicable AEEC, ARINC, ICAO, RTCA and other standards;
e. Use of open standards or company proprietary approaches for avionics design; and
f. Summary of hardware and software architectures employed.

As these six key areas were investigated, two major themes to the research developed. First, multi-modal digital avionics not only has growing acceptance in the industry, it has become the new standard. There are digital avionics in all areas of aviation. New functionality is now possible. Additionally, functionality and modes that once required separate units are performed in single units. Much of the expected functionality of these new systems has been standardized. Display symbology, autopilot features, and very importantly, FMS capabilities, are now well documented in ARINC specifications. As new systems come on line, such as the Terrain Awareness and Warning System (TAWS), these systems are standardized as well. In the air transport category and high-end, business aircraft, this evolution has been steadily progressing from the mid-1980s. In contrast, light general aviation has seen a startling revolution as mechanical flight instruments and analog navigation systems have given way to state-of-the-art flat-panel Electronic Flight Instrument System (EFIS)-type displays in a matter of several years.

Secondly, digital avionics architecture has taken an interesting evolutionary path as it moves away from distributed digital systems that mirrored the architecture of old analog systems (only with digital components), and progresses towards a centralized architecture, more analogous to a modern computer running multiple processes governed by one operating system. The evolution is moving away from the distributed architecture that was used on the MD-11, with all boxes separate and connected with slow ARINC429 data buses. Now Integrated Modular Avionics (IMA) is becoming the mainstream concept. In these systems, the FMS, EFIS, displays, etc. are no longer separate boxes, but rather software on a centralized system. These systems run with a single operating system saving the space and added complexity of having to duplicate hardware and operating systems for all the different applications. This trend has manifested itself on the B-777 and numerous business jet architectures.

However, the simplified hardware architecture tends to complicate the software. New operating systems that must focus on partitioning applications running on a single system are being used. Software is being designed to run on multiple platforms. With software already consuming 70-80% of the development cost of new avionics and with software being the highest risk item in avionics development, some manufacturers wonder if the new focus on minimizing hardware at the cost of additional software is wise. This argument is further supported as the cost of new hardware diminishes and the capabilities rise. In today's computing market the hardware / software cost ratio is approaching a small fraction. These trends have an important effect on new avionics systems design.

1.3   Document Content and Organization

In Section 2 of this report, we provide an overview of all of the multiple functions and integrated features found on the modern air transport. Here, we examine how the avionics components function as a complete system, and we provide an overview of underlying components and their integration.

In Section 3, we continue the discussion by focusing on the Flight Management System, a core element of the modern airline cockpit and one that exemplifies MMDA.

In Section 4, we shift the focus to the evolution of the modern airline transport cockpit. We show how the 1970's vintage airline cockpit has evolved into the modern flight deck. We examine how the original analog systems have been replaced by digital systems, and how analog connections have been replaced by avionics buses such as the ARINC 429 bus. We also introduce the latest trend in digital avionics where multiple software processes are hosted on the same hardware platforms.

In Section 5, we provide an illustrative example of airline avionics evolution by examining the history of the B-737 flight deck.

In Section 6, we examine the McDonnell Douglas MD-11 flight deck, first introduced in 1990. The MD-11 is important to study because it represented the culmination of flight deck integration concepts and ideas conceived in the 1980s. At the time it was the standard to beat. In most respects, it still is, although developments in some areas such as flat-panel displays have gone beyond the 1990s technology of the MD-11 [SP00]. The MD-11 has defined the nature of flight deck automation, and most modern flight decks mirror its architecture and functionality.

In Section 7, we consider the Boeing 777 flight deck. The Boeing 777 flight deck represents the next advance over the MD-11 flight deck. The B-777, with its Honeywell produced flight deck, uses a large-scale integrated computing architecture for airborne avionics. The Boeing 777 Aircraft Information Management System (AIMS) represents the first application of an integrated computing architecture in a commercial air transport.

In Sections 8 and 9, we shift the focus away from the airline cockpit and we examine the avionics packages available for business class and general aviation aircraft. In Section 8, we look at Honeywell and Rockwell Collins avionics systems for business and commuter aircraft. We see how these avionics are used on new aircraft and how they are retrofitted to older aircraft. In Section 9, we examine current day general aviation avionics trends.

In Section 10, we investigate some products produced by manufacturers who build avionics components but have not yet developed an integrated suite of avionics. These manufactures often support the retrofit market where installation of entire suites of new avionics is often not practical. We then discuss the retrofit market for avionics and show how the flight deck of older aircraft can be re-equipped by companies specializing in aircraft renovation.

In Section 11, we look at the most recent trends in avionics. We investigate the views opposing the centralization of avionics and investigate a small but growing trend back towards distributed architectures. Finally, we examine the proposed architecture for the Boeing 7E7, as described by Smiths Aerospace. The architecture utilizes a centralized system, while at the same time taking advantage of recent trends in distributed architectures for handling peripherals.

In Section 12, we summarize elements of the design requirements and guidelines, accepted standards and certification requirements used by avionics manufacturers. Additionally, we address applicable AEEC, ARINC, ICAO, RTCA and other standards.

Section 13 provides our concluding discussion.

2. Sequential or Simultaneous Avionics Operations, Functions and Modes

The modern airline flight deck contains a suite of high technology avionics loosely referred to as cockpit automation. The automation is a collection of displays, controls and computers designed to support the crew in doing the familiar job of piloting and navigating an aircraft while monitoring all of its various systems (see Figure 2.1**Error! Reference source not found.**) and communicating with air traffic control and the airline operations (dispatch) center. In this section we examine the sequential and simultaneous avionics functions and modes that are included within the modern avionics suite.
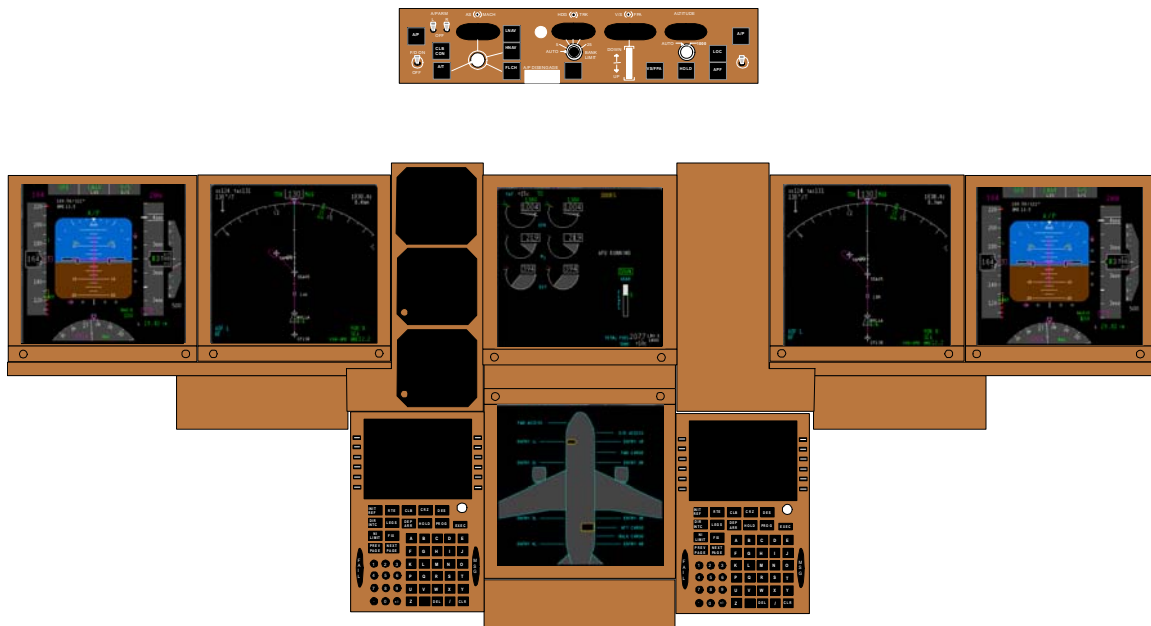
Figure 2.1. Illustration of the major flight deck components of the modern airliner [U02]

The Flight Management System (FMS) is the center of the modern airline flight deck and distinguishes it from earlier cockpits. A basic schematic of a typical FMS installation is shown in Figure 2.2**Error! Reference source not found.**. From the drawing, we see that the FMC interfaces with most other systems on the aircraft. These systems include the Flight Control Computers (FCC), auto-throttle (A/T), all navigation radios, all data link and radio communications systems, and other input/output (I/O) peripherals, such as the electronic flight instruments (EFI) and the fuel quantity indicators.
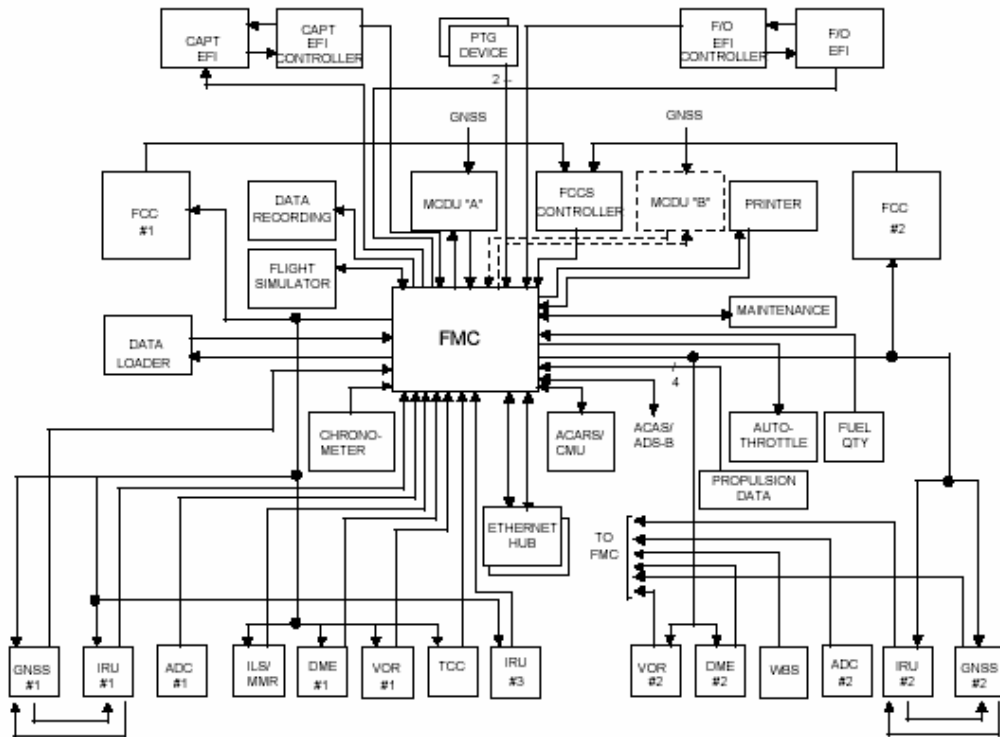
Figure 2.2. Example implementation of an FMS as presented in ARINC 702A-1[ARI00]

This section provides a basic overview of the aircraft systems. A complete operational guide to the modern airline flight deck from the pilot / operator point of view can be found in Casner [Ca01].

2.1 Displays

The modern airline flight deck contains six display screens. While any display screen can be configured to show any display, usually, the displays consist of a Primary Flight Display (PFD) and a Multi-Function Display (MFD) for each pilot, and two Engine Indication Crew Alerting System (EICAS) displays in the center of the console [Ca01].

2.1.1 Primary Flight Display

The primary flight display is a single screen display (see Figure 2.3 **Error! Reference source not found.**) that replaces the classical flight instruments associated with the 'standard six.'[U02] These six include:
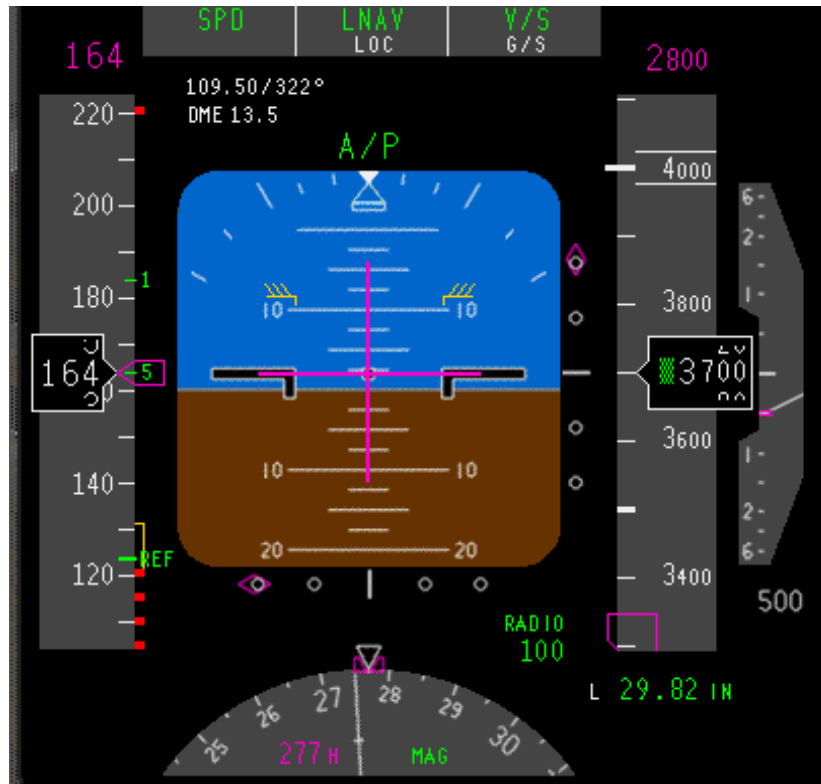
Figure 2.3. Boeing 777 PFD

1. Airspeed;
2. Attitude indicator;
3. Altimeter;
4. Turn coordinator;
5. Directional gyro; and
6. Vertical speed indicator.

The center of the PFD is reserved for a digital attitude indicator which gives a graphical representation of the aircraft's roll and pitch angles. At the bottom of the display, a partial arc icon represents the heading of the aircraft replacing the directional gyro instrument. A moving electronic strip on the right of the display shows altitude. To the far right of the display, a pointer indicates the vertical speed of the aircraft. The left side of the PFD contains the speed tape graduated in calibrated airspeed. The speed tape also contains markings pertaining to speed boundaries (over-speed, stall), and reference speeds used for flap, slat, and gear extension.

In addition to the standard information presented by the classical set of instruments, the PFD also displays a flight mode annunciator at the top of the screen. In particular, the screen indicates the status of the Lateral Navigation (LNAV) and Vertical Navigation (VNAV) systems. The annunciator also indicates the status of the auto-throttle and navigation systems used for approaches (e.g. ILS). When an ILS (Instrument Landing System) is being tracked, the PFD also displays the Course Deviation Indicators (CDI) for both the localizer and the glideslope. The magenta flight director lines in the center of the display indicate the pitch and roll commands

generated by the flight control computer [U02]. Highway-in-the-sky (HITS) flight guidance type displays are often overlaid on advanced versions of the PFD.

2.1.2   Multi-Function Display

The multi-function display is usually used to present the navigation map in the form of an Electronic Horizontal Situation Indicator (EHSI), which presents the 'big-picture' in a graphical format as seen in Figure 2.3. The EHSI shows the aircraft position relative to the route the aircraft is flying. The route, which is typically in the form of a flight plan, is indicated by magenta lines. The fixes (navigation aids such as VORs, route intersections, and waypoints) along the route are represented with the appropriate icon and the associated name of the fix. Additionally, a compass rose is presented at the top of the screen that can be configured to show either ground track or heading. Additional information, such as ground speed and true airspeed, along with the type of navigation aid being used, can also be displayed [Ca01].

Figure 2.4. Boeing 777 MFD [U02]

2.1.3   Engine Indication Crew Alerting System

The Engine Indication and Crew Alerting System (EICAS) consists of many different displays that can be called up and then used by the flight crew for accessing various types of information. **Error! Reference source not found.** Figure 2.4 shows a typical EICAS display that indicates engine performance. Critical engine parameters, such as EPR, N1, and EGT are monitored. Landing gear and flap status are also measured and can be displayed on the EICAS. **Error!**

Reference source not found. Figure 2.5 illustrates the EICAS screen that shows the state of all doors and hatches on the aircraft. The EICAS displays may also contain an electronic checklist to help pilots manage the vehicle systems, and troubleshoot in-flight emergencies [Ca01].
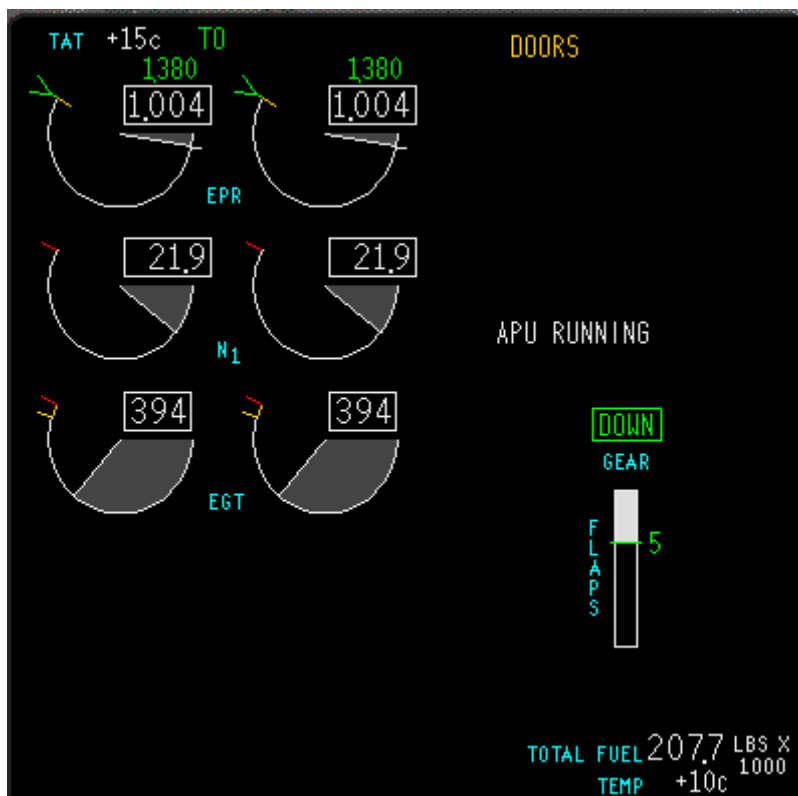
Figure 2.5. Example of Boeing 777 EICAS screen indicating engine performance [U02]
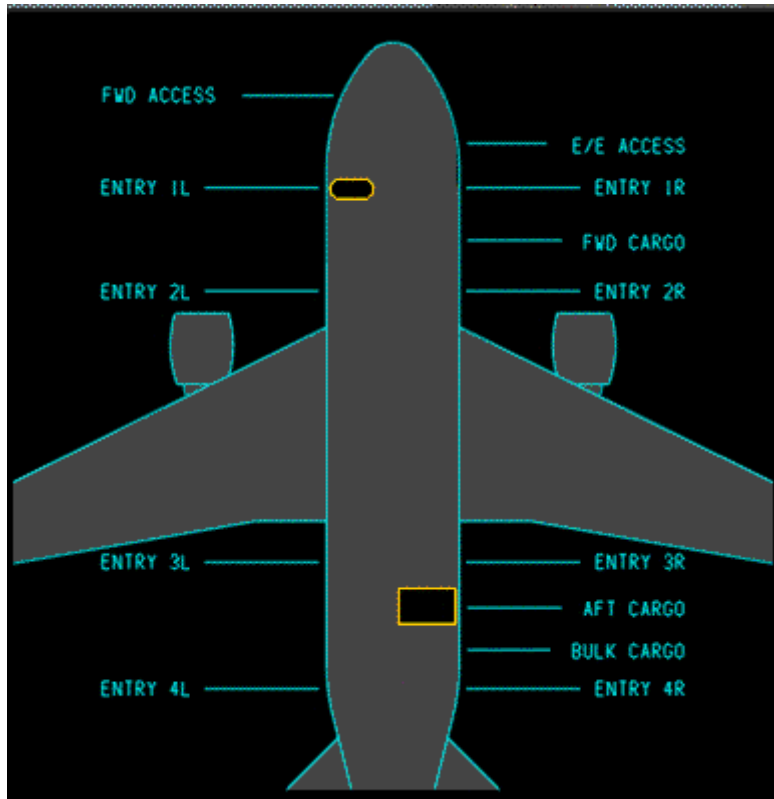
Figure 2.6. Example EICAS screen showing the state of aircraft doors [U02]

2.2 Auto-Flight System and Mode Control Panel

The aircraft's auto-flight system is control provided directly through the Mode Control Panel (MCP), shown in Figure 2.6**Error! Reference source not found.**. The MCP controls the autopilot, the auto-throttle, and flight director. When the autopilot is engaged, the pilot can control the heading, vertical speed, and altitude of the aircraft directly through the MCP. When the auto-throttle is engaged, the speed of the aircraft can be controlled, as well. Additionally, the autopilot can be controlled directly by the flight management system using LNAV and VNAV functions.
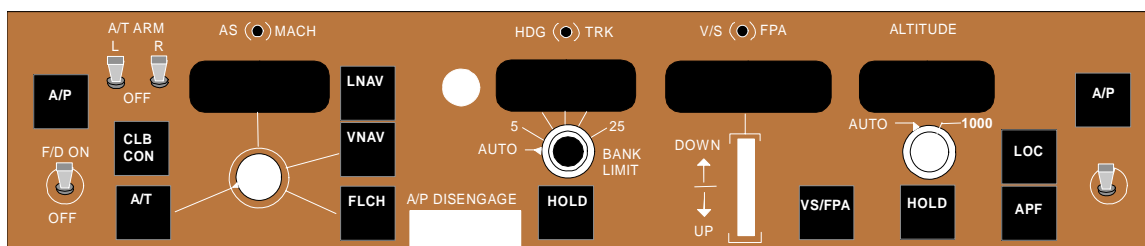
Figure 2.7. Illustration of B-777 Mode Control Panel (MCP)

2.2.1 LNAV and VNAV

When either Lateral Navigation (LNAV) or Vertical Navigation (VNAV) functions are chosen, the FMS is engaged in the guidance of the aircraft. When LNAV is engaged, the FMS guides the aircraft along the lateral path of the active flight plan. When VNAV is engaged, the FMS guides the aircraft along the vertical path, and it maintains the desired airspeed profile. Engaging these functions is accomplished by depressing the LNAV and VNAV buttons on the MCP [Ca01].

2.2.2 Direct Control through the MCP

When the autopilot is engaged and the LNAV and VNAV functions are not activated, the pilot must provide inputs to the autopilot directly through the MCP [Ca01]. This may include setting the desired altitude, heading or airspeed/Mach number.

2.2.2.1 Heading Control

Heading control of the aircraft is accomplished through the heading/track function. The operator dials in the appropriate heading or groundtrack. A toggle switch above the heading control allows the operator to choose between heading and groundtrack. The maximum bank angle limit during turns can also be specified [Ca01].

2.2.2.2 Altitude Control

Altitude control is accomplished differently, depending on whether the auto-throttle is engaged. When the auto-throttle is not engaged, the autopilot only has control over pitch attitude. Under these circumstances, a desired altitude is selected in the altitude control box; however, the aircraft will not start to climb until a vertical speed or flight path angle is specified. The vertical speed control is adjacent to the altitude control. In this situation, if the pilot does not manually add power, the aircraft will reduce speed in the climb.

When the auto-throttle is engaged, altitude changes are accomplished by dialing in a new altitude and engaging the FLCH (Flight Level Change) button. When FLCH is engaged, the aircraft will maintain its current speed during the climb [Ca01].

2.2.2.3 Speed Control

Speed control is only possible when the auto-throttle is armed and engaged. A speed dial then allows the pilot to enter the desired speed. A toggle switch above the speed control allows the operator to choose between units of Indicated Airspeed and Mach number [Ca01].

2.3 Sensors

There are many sensors on board the aircraft that provide input to the avionics functions.

2.3.1 Air Data Inertial Reference Units ADIRU

Large transport aircraft often have an integrated system of sensors called an Air Data Inertial Reference Unit (ADIRU) that collects air data (static and dynamic pressure) in addition to measuring aircraft attitude, velocity and position. These systems' outputs are converted to aircraft state information that is provided to the auto-flight system and to the aircraft displays.

2.3.2 Radar Altimeter

Most modern aircraft use a Radar Altimeter to determine the exact height above terrain when an aircraft is close to the ground.

2.3.3 Weather Radar

Transport class aircraft have some type of weather radar to use for avoidance of convective weather cells. The radar energy is reflected by the water in the cloud formations. Strong returns indicate the presence of heavy rain or hail.

2.4 Flight Management System

The Flight Management System (FMS) is the heart of the modern airline flight deck and distinguishes the modern flight deck from earlier cockpits. The FMS comprises two units, the Flight Management Computer (FMC) and the Control Display Unit (CDU). The Control Display Unit (CDU), which controls the FMC, (see Figure 2.7**Error! Reference source not found.**) provides a keyboard, a numerical keypad, several special purpose buttons, and a small screen for textual messages and inputs to facilitate data entry into the FMS. FMSs have been in use since Honeywell and Smiths introduced them in the 1970's.

The purpose of the FMS is to serve as a navigation, guidance and control aid to the aircraft's pilots. The FMS helps reduce pilots' workload in the areas of trajectory planning, navigation, performance management, guidance of the airplane and monitoring of the flight progress.

The FMS provides a convenient means for the pilots to enter flight plans into the computer which mathematically defines a path from origin to destination. This FMS provides a means for guiding the aircraft automatically along that path while computing and displaying current and predicted progress along the flight plan. The predicted progress is displayed via the trajectory modeling or flight plan following function in the FMS.

To perform these functions the FMS automatically tunes the navigation radios and sets courses which are not necessarily constrained to follow VOR collocated with Tactical Air Navigation System (VORTAC) radials. The FMS also provides automated en route and terminal area guidance using defined procedures. These procedures include Standard Instrument Departures (SIDs), Standard Terminal Arrival Routes (STARs), holding patterns and procedural turns. Data necessary to perform navigation may be supplied by the Navigation Data Base (NDB) which contains information on NAVAIDs, waypoints, Airways, Airports/Runways, Procedures (SIDs, STARs, and Approaches), Company Routes, and Holding Patterns. Recently terrain databases have also become available [CNH97] for increasing flight crew situational awareness.

The modern FMS goes beyond the original guidance and optimization role, and incorporates capabilities for data link for flight plan and weather information updates, and air data /attitude, in addition to the original performance optimization features. Both Smiths and Honeywell are incorporating Required Time of Arrival (RTA) and Required Navigation Performance (RNP) features in their new FMS designs. The FMS is the primary multi-modal avionics system on board the modern transport. Recently the functionality of the FMS has been standardized by ARINC and is published in ARINC 702A-1 [ARI00]. Because of the intricacy of the FMS and the many functions that it performs, a complete discussion of the FMS is contained in Section 3.
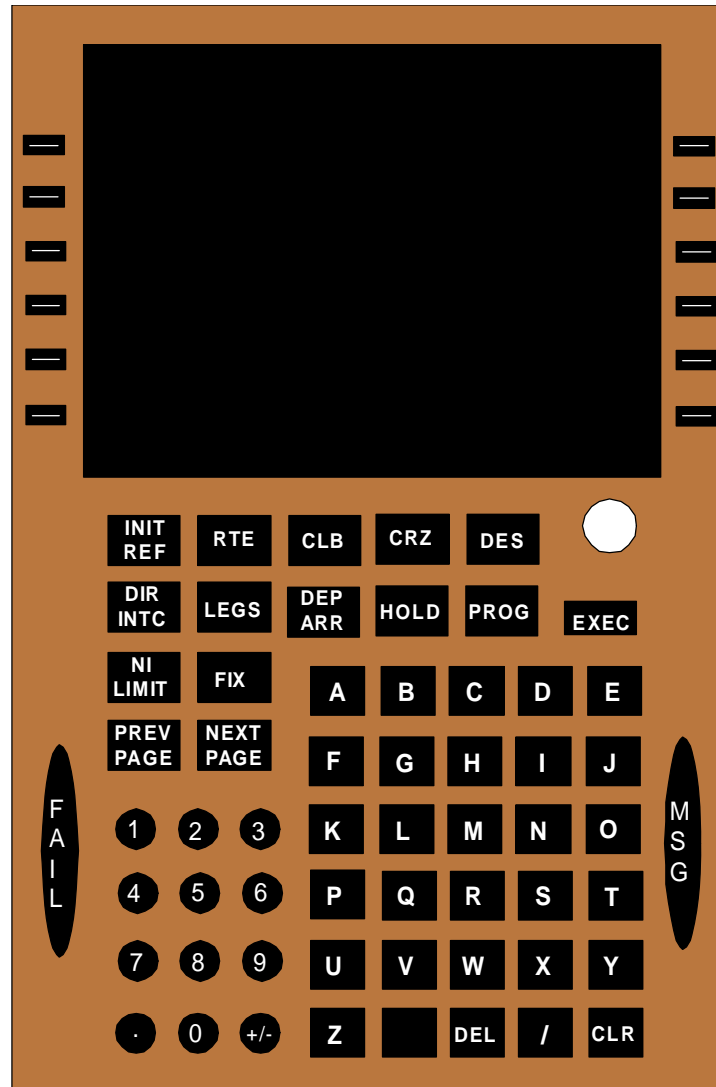
Figure 2.8. Illustration of B-777 Control Display Unit (CDU) [U02]

2.5 Navigation Systems

On the modern airliner, the task of navigation is usually handled by the FMS. The FMS chooses the appropriate navigation systems, auto-tunes the navigation radios and provides LNAV guidance to the auto-flight system. However, when necessary, the pilot can assume manual control over these systems. There are three main navigation systems on board the modern airliner. These are Global Positioning System / Global Navigation Satellite System (GPS/GNSS), VHF Omni-directional Range/Distance Measuring Equipment/Instrument Landing System (VOR/DME/ILS), and the Inertial Reference System (IRS).

2.5.1 GNSS

A GNSS is a space-based radio position, velocity, and time-transfer system. There are currently two operating GNSSs, the Global Positioning System (GPS) developed by the United States and the Global Orbiting Navigation Satellite System (GLONASS) developed by the former Soviet

Republic and being completed by Russia. Each system (GPS or GLONASS) operates independently of the other, although information from both systems may be used in unison to determine position. The European Union is developing a third GNSS referred to as Galileo.

GPS and GLONASS provide the basic signals in space to allow a user to compute their position, velocity and time with a high degree of accuracy. GPS and GLONASS provide signals in space which can be used by anyone. All a user needs is a receiver which is capable of receiving and decoding the signals in space. Both GPS and GLONASS operate in the L-band, and as a result are relatively immune to weather. Each system encodes the signals in space using a spread spectrum technology. GPS standard positioning service (SPS) uses a single frequency and a unique "gold code", i.e., a unique pseudo-random sequence to encode the data. GLONASS uses a single "gold code" and uses 12 frequencies for 24 satellites. Satellites which are directly opposite each other with respect to the earth use the same frequency. Each system transmits, as part of the data, information allowing a user to accurately determine the time of data transmission and ephemeris data, i.e., the data which accurately describes the orbit of the satellite. This provides the user with sufficient information to calculate the precise location of the satellite and the travel time, i.e., distance from the receiver to the satellite. This information can then be used to calculate the receiver location. By observing the Doppler shift of the transmitted signal, the user can accurately determine the instantaneous velocity of the satellite with respect to the receiver. From this information, the user can accurately compute its instantaneous velocity.

Currently, GNSS avionics are not widely used as primary means for navigation on large transport aircraft because the Inertial Navigation System (INS) coupled with DME/DME and VOR/DME in conjunction with the FCC is quite adequate, and because the GNSS signals tend to not be as reliable. The GPS receivers are currently installed on a number of airplanes as supplemental means only, such as B757/767 [CNH97]. However, GNSS avionics are quickly becoming the primary means of en route navigation for light general aviation aircraft.

2.5.2 VOR/DME/RNAV

The VOR navigation system is the primary navigation system existing throughout the world with over 1000 VOR stations in the United States. VOR stations are charted on aeronautical charts and airport guides. Other navigation publications often provide an airport's location relative to a VOR station. The standard airways are based on VOR radials, and frequently begin and end at a VOR station. However, the FAA has plans to phase out use of the VOR.

Developed in the late 1950's and early 1960's, the VOR is more than NDB homing beacons that they replace. When equipped with a VOR receiver, the absolute bearing from the VOR station to the aircraft can be determined rather than the relative bearing available with the NDB. This information can be used to set a course to the VOR station, and the aircraft position can be determined to be on the left or right of the selected course.

Because the VHF signal propagation is line-of-sight, the maximum range of a VOR navigation station depends on the altitude of the aircraft. Typically, the range is about 212 NM at an altitude of 30,000 ft, and reduced to 39 NM at 1,000-ft altitude.

The VOR avionics equipment consists of two components: the omni bearing selector (OBS) and the course deviation indicator (CDI). The OBS is used by the pilot to set the bearing. The CDI has two displays, the 'to-from' indicator that indicates the aircraft's direction to or from the VOR

station, and the signal indicator that indicates whether the received signal is valid (by displaying a red flag when the received signal drops below an acceptable value).

In the operation of DME, paired pulses at a specific spacing are sent out from the aircraft (this is the interrogation) and are received at the ground station. The ground station (transponder) then transmits paired pulses back to the aircraft at the same pulse spacing but on a different frequency. The time required for the round trip of this signal exchange is measured in the airborne DME unit and is translated into distance (nautical miles) from the aircraft to the ground station. Reliable signals may be received at distances up to 199 NM at line-of-sight altitude with an accuracy of better than ½ mile or 3 percent of the distance, whichever is greater. Distance information received from DME equipment is slant range and not actual horizontal distance [CNH97].

Many large airports have VOR facilities on the field that allow aircraft to home directly to the airport. Most small airports do not have such facilities, and navigating to those airports is more involved and time-consuming. The Area Navigation Computer or RNAV, helps the pilot in these situations when the destination is covered within the range of a VORTAC.

The bearing and distance (i.e., the waypoint) of a destination relative to the VORTAC are entered into the RNAV by the pilot. The position of the aircraft is fed continuously into the RNAV by the onboard VOR and DME. The RNAV then supplies the steering information to the pilot to home to the waypoint, as if there is a VORTAC located at the waypoint [CNH97].

On the modern airliner, the intricacies of using these navigation signals and area navigation are handled by the FCC, which then provides a moving map display to the pilot, greatly enhancing the situational awareness to the pilot.

2.5.3   Landing Systems

Landing systems support execution of instrument approach procedures which are classified as either non-precision or precision. A non-precision instrument approach procedure is an instrument approach in which no electronic glide-slope is provided. Examples are VOR, TACAN, NDB, LOC, Airport Surveillance Radar (ASR), Localizer Directional Aid (LDA), or Simplified Directional Facility (SDF) approaches. A precision instrument approach is a standard instrument approach procedure in which an electronic glide-slope/glide-path is provided. Examples are ILS and microwave landing system (MLS). The minimum operating conditions are categorized (see Table 2.1) in terms of Decision Height (DH) and Runway Visual Range (RVR):

Table 2.1. Landing Minimums for Various Landing System Types

Landing Category	DH - Decision Height (ft.) (minimum)	RVR- Runway Visual Range (minimum) ft
Non-precision	Minimum descent altitudes	2400 ft
Category I	200	1800
Category II	100	1200
Category IIIa	50	700
Category IIIb	35	150

Category IIIc	0	0

2.5.3.1   ILS

The Instrument Landing System (ILS) provides an approach path for exact alignment and descent of an aircraft on final approach to a runway.

 The system is divided functionally into three parts:

- Guidance information: localizer, glide-slope;

- Range information: marker beacon, or DME; and

- Visual information: approach lights, touchdown and centerline lights, runway lights.

Both lateral and vertical guidance must be displayed on conventional course deviation indicators or incorporated into multipurpose cockpit displays.

The ground equipment consists of two highly directional transmitting systems and, along the approach, three (or fewer) marker beacons. The directional transmitters are known as the localizer and glide slope transmitters [CNH97].

2.5.4   Inertial Navigation System (INS)

The Inertial Navigation System (INS) is a self-contained navigation system, composed of gyros (or equivalent angular rate sensors), accelerometers, and a navigation computer. The INS computes aircraft position and navigation information in response to signals resulting from inertial effects on system components. An INS does not require information from external references; however, an INS can be aided in updating its position estimates from external sources. The INS is aligned with accurate position and attitude information prior to departure, and thereafter calculates its position as it progresses to the destination. This alignment is done by observing the earth's rotation rate and gravity with the INS's gyros and accelerometers. INS accuracy is very high initially following alignment, and decays with time at the rate between 1 and 2 nautical miles per hour. Position update alignment can be accomplished in flight using ground based or GPS/GNSS references. Ground signals may include VOR, DME, Loran, GPS, or NDB [CNH97].

2.6   Communication Systems

The modern airline cockpit has numerous communication systems including VHF radios for voice communications and digital data link. The VHF voice communications is usually handled by separate VHF radios, while all datalink communications is usually handled by the CMU (Communications Management Unit) or the ACARS MU (Management Unit).

2.6.1   VHF Radios

The most common radio used in aviation is the analog AM, communications radio. In the early days of aviation and radio communication, it was decided that aircraft radios would be operating between 118-138 megahertz hertz range, and due to the fact that most radios were AM "amplitude modulated," so would be the aircraft radio. Therefore, because of tradition and a large intricate legacy system of radios and associated frequencies, aircraft communications devices have remained as old technology AM radios. Earlier, our aircraft communication radios were limited to ninety channels. Modern aircraft radios have up to 760 channels. The aircraft

communication radios operate in what is called the VHF (Very High Frequency) band, which includes the frequencies between 30 and 300 megahertz. The newer communication radios will tune between 118.00 and 136.975 mHz in 25 kHz steps, yielding 760 separate channels.

The pilot of the modern flight deck still typically manually tunes the VHF radios and communicate verbally with ATC .

2.6.2 ACARS Management Unit

The main airline data link which is in operation today is the Aircraft Communication Addressing and Reporting System (ACARS) data link. The ACARS data link ground system is run by ARINC and operates as a service principally to the airlines. Ground operation data link costs are funded by a "fee per message" paid by the users.

The ACARS Management Unit (ACARS MU) is the airborne communications management system that is responsible for the transfer of data between the airborne systems and the ground-based systems using the ACARS protocol.

The ACARS MU can host Airline Operational Control (AOC) or dispatch applications that may have the need to send/receive data to/from the ground-based computer systems. It can also be connected to other onboard computer systems, such as the FMC (Flight Management Computer) which hosts ATC/AOC applications, to serve as a relay function for these computers for air-ground message transfer.

The ACARS MU currently can be connected to the ARINC 716 VHF radio (or ARINC 750 VHF data radio) or the Satellite Data Unit (SDU) to transmit/receive data on VHF or SATCOM data links.

As a communication processor, the ACARS MU can operate seamlessly without peculiarities in any phase. The ACARS MU selects which data link to use depending on the aircraft operating environment (e.g., terminal area versus oceanic). This selection typically is based on airline policy rather than data link performance. For example, although SATCOM provides virtually world wide coverage, it is used only when necessary as it is also the most expensive form of communication.

The ACARS MU hosts a number of AOC applications, which provide services during the terminal and en route phases of flight. The following are common ACARS cockpit crew messages and their uses in different flight phases:

Terminal Area Downlink Messages:

- Terminal weather information;
- Departure delays;
- Clearance requests; and
- Crew payroll reports.

Terminal Area Uplink Messages:

- Fuel uploads;
- Weight and balance;
- Terminal weather information;

- Flight crew schedules;
- Flight plans;
- Gate assignments;
- Departure clearances;
- Passenger lists;
- OUT/OFF/ON/IN times; and
- Fuel on board.

En route Downlink Messages:

- Diversions;
- ETA (Estimated Time of Arrival);
- Security/hijack; and
- Position reports;

En Route Uplink Messages:

- NOTAMS (Notice To Airmen);
- Weather request and information;
- Maintenance;
- Voice contact requests, voice contact;
- Airline Operation Control messages; and
- Free text

For ACARS VHF, the airlines pay a fixed charge per month. The ARINC network charge ranges from $200.00 to $500.00 per aircraft per month depending on the business relationship and total number of aircraft utilizing the service. Besides the fixed charge, airlines also pay 12 cents per 100 characters of user data (also ARINC's price). There is no charge for acknowledgment message that is sent automatically by the ACARS protocol for each user message. The price is independent of distance, i.e., there is no special long distance charge.

Representative SATCOM fees are from 35 cents to 50 cents per kilobit with the average being 40 cents per kilobit. Typical message cost is 50 cents. Unlike the ARINC VHF network, there is no fixed charge for SATCOM. SATCOM charges are all based on a "pay per transmission" structure. Anything that is sent is charged, regardless of user data or network acknowledgments [CNH97].

2.6.3 Controller-Pilot Data Link Communications (CPDLC)

The Controller-Pilot Data Link Communications system is an experimental data link that reduces the number of voice messages by using a special electronic link for routine messages. These messages are digitally displayed on a computer screen in the cockpit. Shifting routine transmissions from voice to data link communications frees up voice frequencies and reduces message delays.

CPDLC achieved initial daily use by controllers at Miami Center on October 7, 2002. American Airlines is the CPDLC launch airline with about two dozen aircraft operating in the Miami

Center airspace. The current organizations intending to outfit aircraft with CPDLC also include: Delta Air Lines, Continental Airlines, FedEx, and the U.S. Air Force.

In the summer of 2003, the FAA announced plans to defer nationwide deployment of data link communications. The agency had planned the first stages of nationwide deployment to its high-altitude control centers starting in December 2005. However, the FAA plans to continue the use of CPDLC at Miami, using aircraft activity there for continued data link research.

On October 6, 2003, Miami Center, American Airlines and the U.S. Air Force completed one year of CPDLC services since achieving initial daily use at the ARTCC. There have been no operational errors or pilot deviations associated with the program equating to 3,173 flight legs of data link transactions resulting in over 40,000 messages being exchanged and 23.8 hours of voice time saved with data link usage. On November 4, 2003, Miami Center began an evaluation of using the data link menu text service to send aircraft direct route clearances. This is the first time a trajectory altering clearance has been issued to aircrews using data link. [FAA04]

2.7 Surveillance and Collision Avoidance Systems

Surveillance in the United States is generally accomplished through the use of primary and secondary radar systems. Participating aircraft must be equipped with either a Mode C or Mode S transponder. Additionally, air transport aircraft are required to carry threat alert and collision avoidance systems (TCAS), a tool for avoiding conflicts with other aircraft.

2.7.1 Mode Select (Mode S) Transponder

Mode S is the latest secondary surveillance radar, an improved version of the Air Traffic Control Radar Beacon System (ATCRBS). Mode S provides improved range and azimuth accuracy compared to the older ATCRBS design. Most transport aircraft are now equipped with Mode S compatible transponders. Mode S operates on the same frequencies as ATCRBS, and can generate the ATCRBS interrogation pattern and accept ATCRBS replies, thus providing complete interoperability for targets which are not yet Mode S equipped. However, Mode S can also generate 4 Mbps DPSK uplink interrogations and accept 1 Mbps PPM downlink replies to support Mode S equipped aircraft. In addition to providing all of the ATCRBS functionality, Mode S provides a general purpose data link. Mode S can provide ground-to-air, air-to-ground, and air-to-air data link for a number of specific services such as TCAS coordination, air traffic control messages, and weather services. Demonstrations of various data being transmitted via Mode S have taken place; however, to date the only data being transmitted via Mode S are surveillance and TCAS data [CNH97].

2.7.2 TCAS

The Traffic Alert and Collision Avoidance System or TCAS provides conflict detection and resolution advisories to the flight crews of equipped aircraft. TCAS uses the secondary radar signals from mode C or mode S transponders to determine range, bearing, and altitude of target aircraft. In current TCAS II logic, only vertical resolution advisories are provided. Due to the limited accuracy of bearing measurements when using Mode S or Mode C, the effect of horizontal miss distance cannot be factored into the modeling calculations. However, if accurate surveillance data could be available in the horizontal dimension, the modeling of vertical Resolution Advisories (RAs) could be performed in three dimensions. The next version of

TCAS, TCAS IV, will use Automatic Dependent Surveillance Broadcasts (ADS-B) and GPS to provide the better horizontal data [CNH97].

3. FMS Functionality as Defined in ARINC 702A-1

This section provides more complete information on the FMS functionality. The FMS is responsible for flight planning, navigation, guidance, and a host of other functions. Recently (2000), the functionality of the FMS was standardized and published in ARINC 702A-1. Under 702A-1, Section 4.3, Functional Description, there are 14 main functions and elements of the FMS. These are:

1. Navigation;
2. Flight Planning;
3. Lateral and Vertical Navigation;
4. Performance (Fuel burn and time of flight) Calculations Function;
5. Printer Function;
6. Airline Operational Control (AOC) Function;
7. CNS/ATM Functions;
8. Airport Surface Guidelines;
9. Terrain and Obstacle Data;
10. Navigation Display Interface;
11. CMU Interface;
12. Predictive Receiver Autonomous Integrity Monitoring (RAIM);
13. Approach and Navigation Database Exchange; and
14. Integrity Monitoring and Alerting.

In this section, we summarize the features of the FMS as described in ARINC 702A to illustrate the magnitude of functionality of the FMS [ARI00], a primary example of MMDA.

3.1 Navigation

The navigation function furnishes continuous, real-time, three-dimensional aircraft state estimate solutions to the crew and provides the following navigational outputs:

- Estimated Aircraft Position (latitude, longitude, altitude);
- Aircraft Velocity;
- Drift Angle (optional);
- Track Angle;
- Magnetic Variation (optional);
- Wind Velocity and Direction;
- Time; and
- Required Navigation Performance (RNP) and an estimate of actual performance.

In system architectures utilizing Inertial Reference System (IRS) sensors, drift angle and magnetic variation may be provided directly by the IRS and are not required to be computed by the FMS.

For vertical navigation, the navigation function provides altitude, vertical speed and flight path angle. Altitude computations operate upon inputs of smoothed inertial altitude from the IRUs, ADIRUs, or AHRS, corrected by barometric (corrected or uncorrected) pressure altitude from the air data system. Flight path angle is derived from vertical speed and computed ground speed. If augmented GNSS altitude is available, it may be combined with the barometric pressure derived altitude to produce a more accurate and stable altitude reference [ARI00].

3.1.1   Multi-Sensor Navigation

The navigation system is designed to select the combination of available sensors that provides the best solution for estimating the aircraft position and velocity. This is an automatic feature and does not require pilot input. Using the sensor accuracy characteristics, sensor raw data, and information about the current conditions, the best combination of position sensors is selected to minimize the position determination error. Usually the FMS will have some combination of the following sensors:

1. (IRU;
2. Air Data Computer (ADC);
3. AHRS;
4. GNSS; and
5. VOR/DME.

As a minimum, the navigation function must provide for GNSS data integrated with a heading / attitude sensor and air data system. Some aircraft installations may not include other navigation radios. Adequate navigation availability must be a consideration in any implementation.

Available navigation sensor data are validated before these are used for updates to the aircraft position. On aircraft with IRUs installed, the primary mode of operation utilizes IRS heading, attitude, position, and velocity, with IRS position and velocity combined with GNSS or VHF radio data from DME, Tactical Air Navigation System (TACAN), VOR, and LOC/ILS. On aircraft without IRUs, the primary mode of operation is position and velocity from available sensors, with heading and attitude being provided from an AHRS or vertical gyro and directional gyro (VG/DG) sources. The filtering algorithm gives appropriate weighting based on the sensor accuracy and provides for sensor error modeling such that the navigation solution accuracy can be maintained through short-term unavailability of various sensors. The navigation function behaves smoothly regardless of sensor availability or sensor transitions [ARI00].

3.1.2   Navigation Modes

With the transition to RNP-based navigation, standardized navigation sensor selection logic is not required; however, a navigation mode sensor hierarchy such as the following may be utilized:

- LOC/ILS (approach only);
- GNSS;

- DME/DME; and
- DME/VOR.

It may be desirable for non-IRU aircraft to correct heading/attitude sensor data based on the other available sensors to provide for a more accurate 'coasting' mode of operation [ARI00].

3.1.3 RNP-Based Navigation

The Required Navigation Performance (RNP) is a means of defining the necessary navigation fidelity for operation within a defined airspace. RNP is specified in terms of navigation information accuracy, containment integrity, containment continuity, and availability of navigation signals and equipment for a particular airspace, route or operation.

The navigation function satisfies the accuracy, integrity and availability criteria set forth for aircraft systems intended to operate in RNP airspace. The system criterion is specified in RTCA documents dealing specifically with RNP and is not part of 702A-1.

The capabilities of the navigation system include position and velocity estimation, path definition and path control and tracking, as well as computing position uncertainty. These capabilities, in addition to a means to evaluate and mitigate flight technical error, form the basis for evaluating and determining total aircraft systems performance for RNP operations. The system must ensure acceptable, repeatable, and minimum error performance. The system accomplishes this by providing clear and unambiguous indications of the navigation situation, including alerting the flight crew when the navigation system does not comply with the requirements of the RNP airspace.

The system provides the appropriate RNP selection and entry capabilities to support determination of the applicable RNP for a flight plan path terminator (leg), procedure, or environment based upon the following, in order of priority:
- Manual RNP entry by the crew;
- Value established in the navigation database for each leg in the flight plan; and
- The default RNP value.

The system provides the capability for stored default RNP values for the various navigation environments (e.g., oceanic, en route, terminal, approach). These values may be established as preprogrammed values and/or loadable into the system [ARI00].

3.1.4 Navigation Alerting and Display

The system provides information which allows the determination that the equipment is functioning properly. The operator must be able to determine the navigation sensors in use and the actual level of navigation performance. The system also provides annunciations and alerting of unacceptable degradation in navigation performance, including alerting to the flight crew when the navigation system does not comply with the requirements of the RNP airspace, routes, and procedures. Some solutions for this might include indications and alerts when the system estimate of position uncertainty exceeds the RNP value. In others, the estimate of position uncertainty and flight technical error may have correlated indications and alerts [ARI00].

3.1.5 Navigation Database

In support of the navigation function, the system must contain an extensive navigation database. This database typically includes the en route, terminal and approach procedures, along with applicable RNP requirements, the navigation aid ground station information, and the procedure-recommended navigation aid (navaid; e.g. DME ground station) information required for flight in the area in which the aircraft operates [ARI00].

3.1.6 Crew Controlled Navigation Functions

Some sensor inputs to the navigation function are capable of being blocked by pilot action in the event that a system-generated message alerts the crew to a problem in the navigation function that the system cannot correct itself. Therefore, manual tuning by the crew of the DME/VOR radios is a feature. If a receiver is being manually tuned, the navigation function continues to auto tune any available channels with station selection as specified for auto tuning. Additionally, DME and VOR navaids may be individually blocked from the navigation solution by entering their identifiers on the Multi-purpose Control Display Unit (MCDU) or by data link. This manual blockage of individual navaids is cleared at flight completion. Capability may also be provided for navigation override where the operator can force the navigation position to coincide with a selected navigation sensor or reference position, e.g., takeoff runway threshold or intersection point. This "position shift" action aligns the "system position" to the selected sensor. Override of navigation position to a manual reference point (e.g. over fly the fix) is inconsistent with RNP operation [ARI00].

3.1.7 Automatic Station Selection

The navigation function selects and tunes appropriate VHF ground radio navigation facilities and uses their position-fixing data to refine the current navigation position. The navaids are those contained within a usable distance from the estimated current aircraft position. This group of navaids, combined with any additional navaids defined by crew entry, makes up the set of navaids from which the best navigation aids can be drawn. With scanning DME installations, up to five frequencies can be allocated to tune each interrogator and, depending upon the aircraft, may be designated for multiple DME range measurements, VOR/DME position fixing, ILS/DME or procedure-specified or pilot-selected navaids. If a procedure being flown has a specified navaid associated with it, then that navaid must be tuned and used for navigation purposes. Station selection criteria are designed to limit station switching activity to a minimum.

DME range measurements received by the navigation function are compared with that of the expected radio range measurement as a reasonableness test. When the comparison is outside of a reasonable tolerance, the data is rejected and not used in the position computations [ARI00].

3.2 General Flight Planning

The flight planning facilities provide for the assembly, modification, and selection of active and secondary flight plans. Various system implementations provide for differing flight planning designations, such as active, modified, temporary, primary, secondary, inactive, Route 1 or Route 2. We consider only primary and secondary plans for the purposes of the discussion. Data can be extracted from the navigation database that contains airline-unique company flight plans,

navigational aids, airways, waypoints, published departure and arrival procedures, approaches, along with associated missed approach procedures, etc. The selection of flight planning data is done through the Control Display Unit (CDU), or through a data link function [ARI00].

3.2.1 Flight Plan State

Once a route is entered or selected as the active flight plan, it becomes the basis from which all guidance and advisory data are referenced. The secondary flight plan can have the same terminus or can be completely different with no shared waypoints. It can be possible to make trial modifications to the active flight plan and review the impact of those modifications without affecting the active flight plan.

For crew review and evaluation, the Electronic Flight Instrument System, or EFIS, (optional) can show the modified flight plan together with the unmodified active flight plan, with unique symbology to differentiate between them. Performance (trajectory) predictions are available on the MCDU for the modified flight plan. During this modification process, all guidance and advisory data is still referenced to the unmodified active flight plan. This modification process may use a separate modified flight plan, or it may make use of the secondary flight plan. If a separate modified flight plan is used, then when all the desired changes have been made, the crew must invoke the modified flight plan to replace the active flight plan. This action will replace the active flight plan and terminate the existence of the modified flight plan. All guidance and advisory data will immediately be referenced to the newly invoked flight plan. Facilities can be provided to access the independent secondary flight plan and to copy this flight plan into the active flight plan when requested by the crew.

These facilities will also be used in modifying the active flight plan, if the manufacturer has opted to use this method to preview flight plan changes, rather than having a separate modified flight plan [ARI00].

3.2.2 Navigation Database

The Navigation Data Base (NDB) contains en route, terminal, and airline custom defined data needed to support the flight management functions. The format of the source data for the NDB is defined in ARINC 424. Each NDB is valid for a specific effective period and is updated typically on a 28-day cycle. The effective dates for a set of data are displayed for reference on the system's configuration definition page. The NDB effective period is compared automatically with the current date and discrepancies are annunciated. The system defines a flight path based on standard ARINC 424 path terminators, as shown next. In the future, only a limited set of these terminator types will be used, as defined by (*); but the system is still capable of manipulating all types:

- AF: DME Arc to a Fix;
- CA: Course to an Altitude;
- CD: Course to a Distance;
- CF *: Course to a Fix;
- CI: Course to an Intercept;
- CR: Course to Intercept a Radial;
- DF *: Direct to a Fix;

- FA *: Course from Fix to Altitude;
- FC: Course from Fix to Distance;
- FD: Course from Fix to DME Distance;
- FM: Course from Fix to Manual Term;
- HA *: Hold to an Altitude;
- HF *: Hold, Terminate at Fix after 1 Circuit;
- HM *: Hold, Manual Termination;
- IF *: Initial Fix;
- PI: Procedure Turn;
- RF *: Constant Radius to a Fix;
- TF *: Track to Fix;
- VA: Heading to Altitude;
- VD :Heading to Distance;
- VI: Heading to Intercept Next Leg;
- VM: Heading to Manual Termination; and
- VR: Heading to Intercept Radial.

Besides waypoints and navaids contained in the database, the pilot has the ability to create new waypoints. These waypoints can be created in a number of ways. Waypoints may be created using Point Bearing/Distance (PBD), PB/PB, Along Track Offset(ATO), Lat/Long pairs, radial crossings, airway intersections, runway extensions or ABEAM facilities, and are stored in the temporary Navigation Data Base [ARI00].

3.2.3 Lateral Flight Planning

Flight plans can be constructed in a variety of ways:
- Navigation Data Base (NDB) procedures;
- Airways;
- Pre-stored company routes;
- Waypoints;
- Navaids;
- Runways;
- Supplemental/temporary waypoints; and
- Combinations thereof.

These selections may be strung together by menu selection from the NDB or by specific edit actions. Flight plans can also be constructed and edited through the data link function. Computations of flight plan magnetic courses utilize an internal magnetic variation model based upon a magnetic variation database.

The NDB procedures consist of (SID), Engine-out SID, (STAR), FMS/RNAV, (GPS)/GNSS, and ILS/MLS.

Holding patterns, and optionally procedure turns, can be defined by database procedure or manually specified, at the current position or any selected waypoint. All parameters for holding patterns or procedure turns are editable, including entry course, leg time/length, etc.

Missed approach procedures can also be included in the flight plan. The missed approach procedures can either come from the navigation database where the missed approach is part of a published procedure, in which case they will be automatically included in the flight plan, or they can be manually constructed by entry through the MCDU. In either case, automatic guidance will be available upon activation of the missed approach. Use of RNP-based FMS and GPS/GNSS approach procedures may not allow manually constructed missed approach procedures [ARI00].

3.2.4 Vertical Flight Planning

Vertical flight planning consists of specification of speed and altitude constraints at waypoints (including At, At or Above, At or Below, and Window constraints), step climbs, (optional) step descents,(optional) cruise climb, tactical changes of speed and altitude and winds at waypoints, and during climb and descent. Facilities are provided for crew selection and entry of various performance constraints:

1. Climb Mode;
2. Cruise Mode;
3. Descent Mode;
4. Hold Pattern Leg Time/Distance/Speed;
5. Airport speed Restriction;
6. Thrust Reduction Altitude;
7. Climb Acceleration Altitude;
8. Performance Correction Factors, such as Drag;
9. Factor and Fuel Flow Factor;
10. Cost Index;
11. RTA Waypoint, Time and Time Tolerance;
12. Climb and Descent Winds;
13. Cruise Waypoint Winds;
14. Temperature; and
15. Tropopause Altitude.

The following additional parameters may also be considered in developing the vertical trajectory:

1. Maneuver Margin;
2. Min Cruise Time;
3. Min Rate of Climb (Clb);
4. Min Rate of Climb (Crz);
5. Min Rate of Climb (Engine out);
6. Anti-Ice Bands; and
7. Step Climb Size and Enterable Default.

3.2.4.1   Wind and Atmospheric Model

Wind and temperature may be entered via the MCDU or data link. The wind model for the climb segment is a set of wind magnitudes and bearings that are entered for different altitudes and horizontal grid points. The value of wind and temperature at any altitude is then computed from these values and merged with the current sensed wind. Wind models for use in the cruise segment allow for the entry of wind (magnitude and bearing) at a waypoint, a single value or multiple wind/altitude pairs. Systems merge these entries with current winds obtained from sensor data in a method which gives a heavier weighting to sensed winds close to the aircraft. The wind model used for the descent segment is a set of wind magnitudes and bearings entered for different altitudes. The value at any altitude is then computed from these values, and merged with the current sensed wind.

A more advanced representation of wind data in the FMC is the use of a grid wind model, which may be up to a four-dimensional (three position coordinates plus time) definition of wind. The grid winds are not tied to waypoints in the flight plan, but associated with latitude-longitude regions, similar to a magnetic variation model. Grid winds would only be uplinked to the FMS rather than manually entered.

Temperature is based on the International Standard Atmosphere (ISA) with an offset (ΔISA) obtained from pilot entries or the actual sensed outside air temperature. The temperature data may be entered associated with flight plan waypoints or as a single value that applies throughout the flight. Likewise, the tropopause altitude (altitude above which a constant temperature is used) may be crew enterable (with36,089 ft. as the default) [ARI00].

3.3   Lateral and Vertical Navigation (Guidance)

The system provides fully automatic, performance-optimized guidance along two-, three-, or four-dimensional paths, defined by the sequence of waypoints specified in the active flight plan. Lateral guidance requires an active flight plan. Vertical guidance requires, as a minimum, an input of gross weight, cost index, and cruise altitude. Air Traffic Control (ATC) constraints may be entered along the flight plan, which in turn will constrain the lateral and vertical flight paths. The FMS guidance drives the Flight Control Computers. The integrated FMS is designed so that the crew can easily override the current guidance commands (without amending the flight plan) for rapid response to tactical situations. The 'intervention' overrides are:

1. Altitude target;
2. Speed target;
3. Course/heading target; and
4. Vertical speed target.

This temporary override replaces the applicable guidance output until the override is terminated, at which point the internally generated guidance commands resume [ARI00].

3.3.1   Lateral Navigation (Guidance)

The lateral guidance of the aircraft is performed using the position data derived by the navigation function and a guidance path generated by the lateral guidance function. The lateral steering function generates a roll command based on these data to guide the aircraft to straight leg

segments between entered waypoints and to transitional paths at the leg intersections. The roll commands generated are constrained by limits imposed by ATC, the flight plan, the automatic flight control system and operational flight characteristics of the aircraft. Special procedural paths such as holding patterns, procedure holds, procedure turns, missed approach procedures and lateral offset paths are automatically flown along with the transitional paths into and out of these procedures.

The aircraft's progress along each path segment is continually monitored to determine when a path transition must be initiated. Direct-to guidance is also available from the aircraft's present position to any waypoint or to intercept a course to or from a waypoint to accommodate modified ATC clearances. LNAV guidance is provided for en route, terminal, and approach area operations, including SIDs and STARs, approaches, holding patterns, lateral offsets, procedure turns, Direct To a Waypoint, missed approaches, etc. [ARI00].

3.3.1.1   Lateral Leg Transitions

Leg-to-leg transitions provide a continuous path between legs and are determined by the course change between the legs, the type of next leg, waypoint overfly requirement, bank angle limitations and the predicted speeds for the transition. Leg transition paths must be constructed within the airspace limitations for operation within RNP airspace. There are three categories of turns recognized in the RNP Minimum Aviation System Performance Standards (MASPS) [ARI00]. These are:

- Fly-by turns--Subdivided into two categories, high altitude (>FL195) and low altitude (<FL195);
- Fly-over turns--Specified as part of leg definition in the NDB, low altitude only (<FL195); and
- Fixed radius transitions.

3.3.1.2   Autopilot Roll Control

Based on the aircraft current state provided by the navigation function and the stored reference path, lateral guidance produces a roll steering command to the autopilot that is both magnitude and rate limited. This roll command is computed to track the straight and curved path segments that comprise the reference path as displayed on the EFIS [ARI00].

3.3.1.3   Lateral Path Reference Displays

Besides generating the roll command, the lateral guidance/lateral steering function also provides outputs relating to the various flight plans for display on the MCDU and the Horizontal Situation Indicator (HSI)/EFIS. These outputs may include:

- Distance to go (active waypoint);
- Commanded course with respect to the leg being flown;
- Downstream leg distances and courses;
- Track angle and track angle error;
- Cross track error;
- Bearings to various waypoints; and

- Lateral track change alert indicators.

This function also supplies data in the form of a complete lateral path to the EFIS such that the flight plan can be displayed in its entirety [ARI00].

3.3.1.4 Path Capture

At engagement, a capture path is constructed that guides the airplane to the active leg. This capture path captures the active guidance leg such that smooth path acquisition occurs without excessive roll activity or turns in the wrong direction. The lateral function also provides guidance during approach for best capture of the LOC/MLS signal, if one exists for the selected approach. Special intercept angle guidance may be provided in some cases to facilitate localizer or MLS capture [ARI00].

3.3.2   Vertical Navigation (Guidance)

The vertical function guides the aircraft to a computed aircraft trajectory that includes all phases of flight. Additionally, all the information necessary for the crew to monitor and control the aircraft vertically is provided. The flight control computer is provided with the vertical guidance control targets and commands necessary for it to control the aircraft to the flight management computed trajectory [ARI00].

3.3.2.1 Trajectory Predictions

The system computes a complete aircraft trajectory along the specified lateral (horizontal) routing. The trajectory includes takeoff, climb, cruise (including cruise and altitude changes) and descent segments that include the approach to a runway, if included in the flight plan. The trajectory is continuous from the origin airport (or current position, if en route) to the destination airport. The trajectory complies with all flight plan specified altitude constraints, speed restrictions and specified gradient constraints. If this is not possible due to aircraft performance or a conflict in the constraints, appropriate advisories are provided to inform the crew of the specific problem.

The trajectories computed for climbing or descending flight are compared against the operating envelopes of the specific aircraft. All trajectories account for the aircraft performance, selected speed schedules and speed transitions, baro-altimeter setting, aircraft flap configuration changes, environmental considerations, intended control mode and other crew vertical flight planning selections, such as reduced thrust operation. The vertical trajectory is integrated with the lateral path in that the distances between lateral waypoints used to compute vertical parameters must account for smooth transitions between lateral legs. The trajectory is updated on a periodic basis, or whenever a flight plan or performance change is made. A trajectory is computed for all flight plans (active, modified, secondary). For each waypoint in the flight plan, the following vertical trajectory data are computed (at a minimum) and made available for display:
- Altitude;
- Speed;
- Estimated Time of Arrival (ETA) or End-to-End (ETE), or both; and
- Fuel on board.

Further, the locations of various vertical trajectory transition points are made available for display. These points may include:

- Speed Change Points;
- Top of Climb;
- Step Climb;
- Top of Descent;
- Vertical Intercept of the Final Approach Segment; and
- Glideslope (or pseudo-glideslope).

These performance predictions are based on the following:

- The lateral and vertical flight plan elements;
- The flight plan legs, including the curved path transitions between legs, holding pattern entries and lateral offsets;
- Entered and measured winds;
- Entered and measured temperature;
- Models of the airplane lift and drag characteristics;
- Models of the engine thrust and fuel flow characteristics;
- Aircraft speed and altitude limitations--margins to stall and buffet onset, VMO (Maximum Operating Speed), MMO (Maximum Mach #);
- Airplane weight and center of gravity;
- Aircraft and engine model adjustment factors (e.g., drag and fuel flow factors); and
- Crew selected and pre-selected guidance modes.

3.3.2.2 Vertical Guidance

When a managed mode of vertical guidance is selected, the FMS provides commands of pitch, pitch rate and thrust control to the parameters of target speeds, target thrusts, target altitudes and target vertical speeds (or alternatively may provide only the targets, depending on the selected vertical mode and the flight management/flight control architecture of the particular aircraft). Vertical guidance also provides mode commands for the flight control computer and thrust management functions, as well as automatic flight phase switching. The vertical profile upon which the vertical guidance is based is the trajectory prediction defined previously. The vertical guidance functions provide for auto switching of the flight phase during a flight. This flight phase is used as the basis for speed and thrust target selection and is made available to the flight control computer. At a minimum, the system provides logic for the transition between flight phases for preflight, climb, cruise and descent. The preflight phase applies when the aircraft is on the ground and allows for access to and entry of all flight management initialization data. After lift off, the phase switches to climb, and the climb phase remains active until the aircraft reaches the top of climb, at which point the phase switches to cruise. The phase then switches from cruise to descent when the aircraft reaches the top of descent, and the descent phase remains active for the remainder of the flight.

Since altitude clearances are difficult to pre-plan using flight plan altitude constraints, a crew-selected altitude, usually provided by the flight controls panel, is used as a tactical altitude

limiter by the flight management function. The aircraft, under vertical guidance control, is not allowed to climb through the selected altitude during a climb, or descend through the selected altitude during a descent. During approach operations, this general rule may be suspended to allow the crew to pre-select the altitude clearance to arm a missed approach. The selected altitude may also be used to arm an automatic transition to descent or to enable step climbs and descents during cruise phase operations [ARI00].

3.3.2.3   Speed and Altitude Restrictions

Speed and altitude restrictions encountered in the climb are observed by the vertical function to prevent the aircraft from accelerating or climbing beyond those restriction values until the associated restriction has been passed. At this point the next restriction (if any) becomes the limiting case. Restrictions encountered in descent are handled similarly, except that in the case of speed restrictions, sufficient deceleration distance must be provided in order to achieve the restrictive speed prior to passing the associated restriction [ARI00].

3.3.2.4   Required Time of Arrival (RTA)

The system has the ability to guide the aircraft to any specified waypoint at a specified time. Accuracy of this function is ±30 seconds en route and ±5 seconds in the terminal area. If the RTA is predicted to be not achievable, an annunciation of the problem to the crew is provided. The situation is continually reassessed until such time as the RTA is achievable. While on the ground, the system computes the takeoff time window that allows an achievable time at the specified RTA waypoint. All RTA calculations respect speed envelope restrictions as well as all flight plan constraints. The RTA control band is designed to limit throttle activity to a minimum. This function accommodates ATS data link of RTA constraints consistent with RTCA DO-219, including constraint types At, Before, After, and Between. Systems may provide RTA predictions showing the earliest and latest times the aircraft may arrive at a waypoint (an RTA window). Also, consideration of fuel reserves in the prediction of RTA feasibility may be provided [ARI00].

3.3.2.5   Three-Dimensional RNAV Approach

The system provides the facilities to integrate into its trajectory, a three-dimensional approach path to the runway threshold. This path is constructed in the vertical plane based on a geometric gradient. The source data to create this gradient path is retrieved from the navigation database records when an approach is selected or provided via data link. The format of the source data is specified in ARINC 424. The system provides for the selection of a landing speed consistent with the planned flap selection and wind corrections. The landing speed is used in computing the three-dimensional approach trajectory. The system provides lateral and vertical navigation, including speed targets, to this approach trajectory and provides flap extension advisories, as well as advisories for additional energy bleed-off, if required [ARI00].

3.3.3   Performance Modes

The pilot has many different performance modes to choose from when flying a route. Eighteen modes are now described.

3.3.3.1 Economy Speed Mode

One performance mode that is common to all flight phases is the "economy" speed mode, which calculates the associated speeds and speed schedules that minimize the total cost of operating the airplane on a given flight. This mode uses a Cost Index, which is the ratio of time-related costs (crew salaries, maintenance, etc.) to fuel cost. This is expressed as:

$$\text{Cost Index (CI)} = \text{Time Cost / Fuel Cost}$$

Typical Cost Index entries vary from zero to 999, with the minimum trip fuel cost occurring with the Cost Index set to zero. Cost Index values above zero result in increased trip speeds and varying aircraft vertical trajectories, as the cost of time is valued more. At the proper Cost Index, the increased fuel cost is offset by the reduced time cost.

3.3.3.2 Climb Mode

Speed modes supported in a climb include:

- Economy CAS/Mach (based on Cost Index) - Lowest cost of operation;
- Pilot-entered Computed Air Speed (CAS)/Mach - Manual selection;
- Maximum angle climb - Maximum climb rate with respect to distance;
- Maximum rate of climb - Maximum climb rate with respect to time; and
- Required Time of Arrival (RTA) - Variable speed to meet a time constraint.

3.3.3.3 Cruise Mode

Speed modes supported in cruise include:

- Economy CAS or Mach (based on Cost Index) - Lowest cost of operation;
- Pilot-entered CAS or Mach - Manual selection;
- Maximum endurance - Maximum time endurance;
- Long Range Cruise - Maximum range;
- Required Time of Arrival (RTA) - Variable speed to meet a time constraint; and
- Step Climb and Step Descent (for changes in cruise flight level).

3.3.3.4 Descent Mode

Speed modes supported include:

- Economy CAS/Mach (based on Cost Index) - Lowest cost of operation;
- Pilot-entered CAS/Mach - Manual selection;
- Maximum descent rate - Maximum descent rate with respect to time; and
- Required Time of Arrival (RTA) - Variable speed to meet a time constraint.

A descent path is computed based on the economy speed schedule, manually selected speed schedule and complying with waypoint speed/ altitude constraints, where the path is defined as the altitude and speed as a function of the distance from the destination. This path is constructed such that the performance of the aircraft is optimized with respect to the cost index, assuming the aircraft will be allowed to follow the constructed path [ARI00].

3.3.3.5 Maximum and Optimum Altitudes Calculation

The performance function computes both optimum and maximum altitude for the aircraft/engine type, weight, atmospheric conditions, bleed air settings and the other vertical flight planning parameters. The optimum altitude algorithm computes the most cost effective operational altitude, and the maximum altitude algorithm computes the highest attainable altitude, while allowing for the specified rate of climb margin [ARI00].

3.3.3.6 Trip Altitude Calculations

The performance function computes a recommended cruise altitude for a specified route. This altitude may be different from the optimum altitude, in that for short trips the optimum altitude may not be achievable, because of the trip distance. This algorithm searches for the altitude that satisfies the climb and descent segments while preserving a minimum cruise time specified by the crew or airline policy. Some FMS designs elect to integrate this computation as part of the optimum altitude algorithm. All the vertical flight planning parameters are considered in this algorithm [ARI00].

3.3.3.7 Alternate Destinations Calculation

This performance function performs alternate destination calculations. The computations are optionally based either on a direct route from current position to the alternate destination or continuing to the current destination, execution of a missed approach at the destination and then direct to the alternate destination. Distances, fuel, ETA, and optionally best trip cruise altitude for selectable alternate destinations are computed and available for display. Also computed for these alternate destinations are available holding times at the present position and the current fuel state versus the fuel required to fly to alternates. Additionally, this function provides for the retrieval of the airports nearest the aircraft at crew request [ARI00].

3.3.3.8 Step Climbs and Descents

The performance function includes a prediction of the optimum point(s) at which a step climb/descent maneuver may be initiated to provide for more cost effective operation. This algorithm considers all the vertical flight planning parameters as well as entered wind data. The time and distance to the optimum step point to the specified step altitude is made available for display. Also, the percent savings penalty for the step climb or descent versus the current flight plan is computed and displayed [ARI00].

3.3.3.9 Cruise Climb

The performance function computes optimum cruise climb guidance parameters for all-engine and engine-out conditions. This algorithm takes into account fuel burn (weight decrease) and the predicted wind altitude profile. Automatic mode transition to level cruise occurs when an altitude constraint is reached [ARI00].

3.3.3.10 Top of Climb/Descent Advisories

The performance function computes distances to the top of climb (T/C) and top of descent (T/D) points. This information is based on the stored trajectory prediction and the current state of the aircraft. Also, for the climb and descent phases, performance computes the distance and ETA to the next altitude constraint. In descent, the distance and ETA is computed for the next intermediate T/D (where the aircraft will continue its descent after a level-off in the descent path caused by an altitude constraint) [ARI00].

3.3.3.11 Thrust Limit Calculations

The thrust limits for takeoff, climb, cruise, go-around and continuous modes of operation are computed (if applicable for the installation) for the current atmospheric conditions and type of engine/aircraft and bleed settings. Moreover, de-rated performance for takeoff and climb thrust are made available for selection, as well as selected temperature de-rated for takeoff thrust. The crew can manually select the thrust limit mode that is output as the current thrust limit, or an auto mode can be selected that makes the choice based on logic between the flight control computer and the FMC.

In some designs the thrust limit function is performed by a Thrust Control Computer (TCC). For these designs, the thrust limit computation in the FMC is only used for trajectory predictions and to support other performance calculations [ARI00].

3.3.3.12 Takeoff Reference Data

The performance function provides for the computation, or entry, of V_1, V_R and V_2 takeoff speeds for selected flap settings and runway, atmospheric and weight/center of gravity (CG) conditions. These speeds are made available for crew selection as output for display on the flight instruments. In addition, takeoff configuration speeds are computed and displayed for reference [ARI00].

3.3.3.13 Approach Reference Data

Landing configuration selection is provided for each configuration appropriate for the operation of the specific aircraft. The crew is allowed to select the desired approach configuration, and the state of that selection is made available for output to other systems. Selection of an approach configuration also results in the computation of a landing speed based on a manually-entered wind correction for the destination runway. Additionally, approach configuration speeds are computed and displayed for reference [ARI00].

3.3.3.14 Reserve Fuel Calculation

The amount of fuel that can be specified as reserve fuel is computed based on the estimated fuel burn for the active flight plan and the entered/measured total fuel quantity. This computation may be used as a default reserve fuel value. Manual entry of a reserve fuel quantity to override this computation is provided [ARI00].

3.3.3.15 Engine Out Performance Calculation

Systems provide engine-out performance predictions for the case of the loss of at least one engine. These predictions may include:

- Climb at engine-out climb speed;
- Cruise at engine-out cruise speed;
- Drift down to engine-out maximum altitude at drift down speed;
- Use of maximum continuous thrust; and
- Two-engine-out predictions when applicable on three- and four-engine aircraft.

3.3.3.16 Maximum Range Computation

The capability to compute the maximum range of the aircraft based on the entered/measured fuel quantity and the specified reserves is provided. Both range to reserves and range to empty may be displayed as appropriate.

3.3.3.17 Maximum Endurance Calculation

The maximum endurance time of the aircraft may be computed based on the entered/measured fuel quantity and the specified reserves. Both endurance time to reserves and time to empty can be provided.

3.3.3.18 Descent Energy Circles

For a selected fix point and associated altitude constraint, the distance required to descend from current altitude to the constraint altitude can be computed for both 'clean' and 'full drag' aircraft configurations. These data can be available for display on both the MCDU and as range circles centered on the specified fix on the navigation display [ARI00].

3.4 FMS Printer Function

A printer is provided to print various data such as data link messages, flight plans, and maintenance information.

3.5 Airline Operations Control (AOC) Function

The system provides for a data link interface with the Airline Operations Control (AOC) center, or dispatch function. This interface allows for uplink and crew-controlled insertion of parameters that are enterable through the MCDU. This includes:

- User-preferred flight plans defined by the airline dispatch office;
- Wind profiles at multiple altitudes;
- Waypoints where automatic position reports are required;
- Performance initialization data;
- Navigation database amendments; and
- NOTAMs.

Likewise, this interface provides for the downlink of data computed for display on the MCDU, including flight plan requests and waypoint reports.

3.6   CNS/ATM Functions

The Air Traffic Services (ATS) providers are implementing, or have plans to implement, Communication, Navigation, Surveillance/Air Traffic Management (CNS/ATM) functions using existing and future data link systems. These data links include:

- ARINC 618 and 620 (ACARS);
- ARINC 622;
- Aeronautical Telecommunications Network (ATN) Broadcast Data Link; and
- Mode S Specific Services.

The FMS system supports communication functions operating over all of these data links. For some proposed architectures the CNS/ATM functions may be performed in whole or in part by units other than the FMC. The discussions in these sections apply primarily to architectures for which the FMC serves as the end system for the function. For other architectures where the ARINC 758 CMU is the end system, the FMC provides interface data to support the application in accordance with ARINC Specification 656.

3.6.1   CNS/ATM Functions using ACARS

CNS/ATM functions which are character encoded and transmitted over ACARS are specified in ARINC 623. These include:

- Pre-departure Clearance (PDC);
- Oceanic Clearance Message (OCM) for North Atlantic operations; and
- Automatic Terminal Information Service (ATIS.)

Other functions being planned include:

- Terminal Weather Information for Pilots (TWIP); and
- Taxi Clearance.

All of these functions are defined as printer compatible, character encoded messages and are not compatible with automatic loading. Clearance data and weather data in these messages must be manually loaded by the pilot.

3.6.2   CNS/ATM Functions using ARINC 622

ARINC 622 defines how binary formatted CNS/ATM functions are transposed into hexadecimal characters and transmitted over ACARS, Satellite Communication (SATCOM), and HF data links using the service provider networks e.g., ARINC, SITA, Air Canada, AVICOM, etc. The system supports the following ARINC 622 mechanized functions:

- ATS Facilities Notification (AFN);
- ADS (RTCA DO-212 and ARINC 745); and
- Controller/Pilot Data Link Communication (CPDLC) (RTCA DO-219).

3.6.3 Aeronautical Telecommunications Network (ATN)

The system supports the CNS/ATM functions being defined in the ICAO CNS/ATM-1 SARPS. These include:

- ATN;
- Data Link Initiation of Communications (DLIC);
- CPDLC;
- ADS; and
- Flight Information Service (FIS).

ARINC 660 defines possible avionics architectures for implementing CNS/ATM functions. There are three architectures which impact the roles of the FMS and the ARINC 758 CMU in an ATN data link environment. These are:

- FMS is the ATN and application end system, and the CMU is an ATN router. The ARINC 656 FMS/CMU interface is used;
- FMS is the application end system. The CMU is the ATN end system and gateway to the FMS, using the ARINC 656 remote stack interface; and
- CMU is the ATN and application end system, i.e., single end system. The FMS supports the ARINC 656 interface as required.

The following sections primarily define the requirement for the FMS when it is the application end system. ARINC 656 defines the responsibilities of the FMS and CMU to support the interface between them.

3.6.4 Broadcast Data Links

Potential applications for broadcast data links include:

- Surveillance by ADS-Broadcast;
- Air-to-air conflict resolution;
- Ground-to-air traffic information;
- Hazardous weather alerts; and
- Atmospheric data.

Broadcast data link using Mode-S Extended Squitter, Universal Axis Transceiver (UAT) and VHF Time Division Multiple Access (TDMA) are all being applied. The Mode-S service system provides data to support Mode-S data link services when defined. Current Mode-S definition is provided by ICAO document "Manual on Mode-S Specific Service" issued by SSR Improvements and Collision Avoidance Systems Panel (SICASP)/5.

3.6.5 Controller/Pilot Data Link Communication (CPDLC)

In the interim ATS communications environment with ARINC 622, the CPDLC specific messages supported are those defined by RTCA DO-219. These messages include some which are loadable and others which are display only. The FMC provides for the capability to receive and send these messages over the data link channel defined in Section 3.6.2. The FMC provides the capability to interface with the network protocol and integrity checking.

3.6.6 Crew Interface and Operation

Interpretation of the message is based on the CPDLC application defined by RTCA DO-219 or CNS/ATM-1 message element number. Upon receipt of an ATC uplink, the system annunciates an alerting level message in the primary field of view and sets an output discrete that is used to control an aural warning. These messages may be of the form ATC X, where X can be ROUTE, ALTITUDE, SPEED, etc. The system also provides for a crew interface that details these messages for crew review along with the appropriate prompts for crew responses, such as accept, reject, standby or response data that may be required.

3.6.7 Flight Plan Automatic Loading

As a minimum, the FMC functions provide the capability to automatically load the following message types: RTA waypoints, required times, lateral offsets, flight plans and modifications. For all autoload functions, the changes are displayed for review of the effect of the changes by the flight crew. The changes are activated upon positive confirmation from the crew.

3.6.8 ADS and ADS-B

The FMS supports ADS-B and provides for the "Periodic Contract," "On Demand Contract," "Event Contract," Emergency Reports, "Cancel Contract," and "Cancel All Contracts and Terminate Connection" uplink messages, as well as "Acknowledgment," "Negative Acknowledgment," "Noncompliance Notification," and data downlink messages as defined in ARINC 745 and DO-212. This function supports connections to at least one AOC and four ATC centers, each of which can have one contract of each type and report the right data to the right one at the right time. In the interim ATS communication environment, the ADS applications are supported using ARINC 622 data links.

The ADS contracts are established automatically by the contract protocol defined in ARINC 745 without the need for crew intervention. Each contract specifies the data groups as well as the report interval and other report downlink triggers that are desired. Until superseded by the ATN, the ADS function must keep track of the ATC center address of each of these centers. All time stamps associated with data groups are based on the UTC received from the GNSS. UTC based on aircraft clocks are only used in case of GNSS outage or failure. The FMS also provides a crew interface for the control and display of the ADS function. The FMC provides position / altitude / time and intent at a specified interval, depending on whether flying terminal, en route, oceanic or domestic. It also allows continuous conflict predictions to be performed on the ground by ATM and by other aircraft. This broadcast message is being defined by RTCA SC-186 MASPS and may include:

- Position (latitude and longitude or possibly earth centered position vector);
- Altitude;
- Time stamp;
- Velocity vector (3D);
- Intent data in the form of waypoint positions, altitude, and ETA;
- Selected altitude and ETA (if climbing or descending);
- RNP; and

- Estimate of actual performance with respect to RNP.

3.6.9 Free Flight Support Functions

It is unclear to what extent Free Flight is going to be adopted into the NAS; however, many of the 'required' features to implement Free Flight already exist. The "Final Report of RTCA Task Force 3, Free Flight Implementation" was released on October 26, 1995. It defines Free Flight as

> "a safe and efficient flight operating capability under Instrument Flight Rules (IFR) in which operators have freedom to select their path and speed in real time. Air traffic restrictions are only imposed to ensure separation, to preclude exceeding airport capacity, to prevent unauthorized flight through Special Use Airspace (SUA), and to ensure safety of flight. Restrictions are limited in extent and duration to correct the identified problem. Any activity which removes restrictions represents a move toward free flight".

The Free Flight report identifies a three-phase program to achieve the goal, with continuing evolution. These phases are:

- Phase 1--Near Term (through 1997);
- Phase 2--Mid Term (1998 through 2000); and
- Phase 3--Far Term (2001 and beyond)

Each phase addresses the multiple domains of domestic en route, terminal including airport ground operations, oceanic, and the preflight traffic flow management collaborative processes.

In Phase 1 the existing capability of aircraft equipage, especially the ARINC 702 FMCS, were to be exploited.

In Phase 2, the additional capabilities defined in ARINC Characteristic 702A, including Controller/Pilot Data Link Communications (CPDLC) and Automatic Dependent Surveillance (ADS) were to be required.

Phase 3 requires additional functionality in the form of ADS Broadcast (ADS-B) to provide enhanced surveillance. Note that RTCA SC-186 is responsible for the definition of ADS-B. The transition from ACARS supported by ARINC 622 data links to the Aeronautical Telecommunications Network (ATN) is expected in Phase 3.

The development of free flight is likely to follow independent paths in the USA domestic and the international oceanic airspaces. Because the free flight operational concept goes beyond that envisioned by the ICAO FANS concepts, considerable international debate is expected. The Task Force No. 3 report identifies numerous FMC functions which may be required to facilitate the transition to a free flight environment. These include:

- Area navigation (RNAV) providing optimum lateral and vertical trajectories;
- GNSS navigation sensors and time reference;
- RTCA SC-181 compliant navigation (RNP);
- Automatic monitoring of available navigation performance vs. required RNP;
- Data linking of trajectory and winds (AOC automatic flight plan loading);
- Direct Controller/Pilot Data Link Communications(CPDLC) (with ATS automatic route clearance loading);

- Required Time of Arrival (RTA) capability to +/- 30 sec. en route,   +/- 5 sec. terminal;
- Ability to designate, create, or modify a waypoint using the navigation (map) display and a pointing device;
- Separation assurance from terrain and fixed obstacles;
- Consideration of Special Use Airspace and FIR boundaries;
- Airport surface maps with taxi guidance; and
- Surveillance data for ADS and ADS-Broadcast (including state, intent, and deviation from intent).

Many of these features exist today, but it is unclear to what extent they will be able to contribute to the future Free Flight [ARI00] paradigm as in evolves**.**

3.6.10 ACAS Interface

The role of the FMS and the standard interface between an Aircraft Collision Avoidance System (ACAS) or Traffic Alert and Collision Avoidance System (TCAS) unit and the flight management function has not been defined [ARI00].

3.7   FMS Airport Surface Guidelines

Currently, ARINC has no standard for airport surface guidance features, but future additions will likely have standards pertaining to surface navigation guidelines.

3.8   Terrain and Obstacle Data

Currently, ARINC has no standard for this type of feature, but future additions will likely have standards pertaining to terrain and obstacle data. However, the database is relatively well defined.

The terrain and obstacle database provides terrain and obstruction clearance information. The airport surface map database may contain data describing all supported airport surface maps which can be utilized to navigate aircraft along the airport surface in both Visual Meteorological Conditions (VMC) and low visibility conditions. The airport surface map database may include the following:

- Runways and Runway direction;
- Taxiways;
- Hold short locations;
- Taxiway Locator;
- Taxiway Ending Markers;
- Taxiway direction;
- Apron;
- ILS/MLS holding positions;
- Runway Safety Areas and Runway Approach Area;
- Boundaries;

- Intersections;
- Aircraft Fueling and Service areas;
- Gate location and number;
- Civil aircraft operations areas;
- Military aircraft operations areas;
- Cargo handling areas; and
- International Flights areas.

3.9 Navigation Display Interface

The system provides for an interface with an Electronic Flight Instrument System (EFIS or EIS) for the purpose of supporting the navigation data display described in this characteristic. This includes the standard interface between the EFIS and the flight management function, detailing the interface data and formats, etc. In addition to the map background data, the system supplies a number of other data items that are shown on the navigation displays. These may include:

- Wind (either cross wind and headwind components or magnitude and bearing);
- Time and distance to go to the next waypoint;
- Ground speed;
- Vertical deviation when guiding to the descent path; and
- Trend vector showing current rate and direction of turn.

Independent displays are provided for the pilot and copilot by each of the two Flight Management Computers. Thus, each pilot may select different map ranges, modes, or options [ARI00].

3.10 CMU Interface

The system provides for an interface with a CMU for the purpose of supporting all data link functionality as defined in ARINC 702a.

3.11 Predictive Receiver Autonomous Integrity Monitoring (RAIM)

Optional capability may be provided for the FMS to transmit the selected destination latitude, longitude, and ETA to the GNSS when a flight plan has been activated and predicted. The purpose of this capability is for the prediction of the availability of GNSS satellite coverage for the approach phase of the flight. The GNSS responds to whether adequate satellite coverage is anticipated. If not, the system immediately alerts the crew. Interface requirements for this capability are defined in ARINC Characteristic 743A, Appendix C.

3.12 Approach and Navigation Data Base Exchange

Recommendations for this function will be provided in a future Supplement to this Characteristic. One possible implementation of this function provides for the FMC to transmit to the GNSS landing function the final approach path data packet as extracted from the FMC navigation data base when the approach has been selected and the GNSS landing function has

been armed for the approach. The final approach data packet would include a 32 bit Cyclic Redundancy Check (CRC) value to ensure the integrity of the packet that was preserved from the time of the original packet generation.

3.13 Integrity Monitoring and Alerting

The integrity, monitoring and alerting features check the internal function of the FMS and alert the pilot to system status and failures. This includes the following three functions.

3.13.1 Sensor Status

Sensor warning inputs are implemented as specified in ARINC Specification 429, Section 2.1, in that validity status is contained within the digital word format. In all cases of sensor input failure, suitable sensor failure warning and degraded status annunciation are provided.

3.13.2 System Status Alert

Any change of status that results in reduced system operational capability or availability is annunciated to the pilot on, or adjacent to, primary flight instruments. Additional data for use in diagnosing the reason for the change is displayed on the MCDU or output to an onboard printer of the data collection system (e.g., through the data loader interface). Means are provided to cancel the alert. The system status alert is designed only to attract the attention of the pilot to the fact that something has happened either within the system or to one of the sensors that has degraded or will degrade the operational viability of the system.

The FMC is designed to perform automatic self tests of its internal operation, and reasonableness tests on input data during normal operation. The FMC generates digital output messages which include malfunction codes to indicate the FMC's assessment of its health and the status of its interfaces.

3.13.3 Failure Response

The system monitors its own health and processing for integrity. When an error is detected, the system records the failure in a nonvolatile BITE log and attempts to recover from or correct the error if possible. If an attempted fault recovery is unsuccessful, the system prevents further processing in the affected partition. The airlines desire a high degree of fault tolerance in the FMS. System recovery logic for intermittent faults is designed to minimize visible flight deck effects and loss of system availability [ARI00].

4. Evolution of Large Transport Aircraft Flight Decks

To fully understand the integrated modes and components included in today's flight deck avionics systems and what future innovations are likely, it is instructive to examine the evolution of flight decks, beginning with 1970's vintage aircraft when the FMS first appeared. In this section we trace the events of the last 30 years that have brought the industry to its current state.

First, we look at the general architecture for these airplanes as they progressed through four important phases of development. Finally, we examine the fifth and future phase of development. To illustrate the important changes throughout the evolution of the flight deck, several simplified, hypothetical flight deck architectures are presented. The drawings do not accurately portray any real flight deck.

4.1 Evolution of the Airliner Flight Deck

Since the 1970s, the general architecture of airliner flight decks has progressed through four major phases of development. These are:

1. Electromechanical (non-FMS);
2. Electromechanical with FMS;
3. Hybrid / EFIS with FMS;
4. Fully digital, distributed, glass cockpit.

A fifth phase of development currently represents state-of-the-art thinking in flight deck design and has been partially implemented on aircraft such as the B-777:

5. Centralized Computing Architecture.

4.1.1   Electromechanical (non-FMS)

The electromechanical flight deck of the early 1970s (see Figure 4.1) consisted of electromechanical air data instruments such as airspeed, Mach, and altimeters and mechanical attitude gyros. The flight deck was automated with an analog autopilot and auto-throttle. The navigation instruments consisted of VOR/DME/ADF type instruments and needed to be manually tuned. Once tuned properly, the autopilot could be used to track the navigation signals for automated guidance. An inertial reference system might be present. Engine and system instruments were manually monitored. Aircraft often required an additional crewmember to serve as flight engineer to monitor the aircraft systems. All connections were analog.
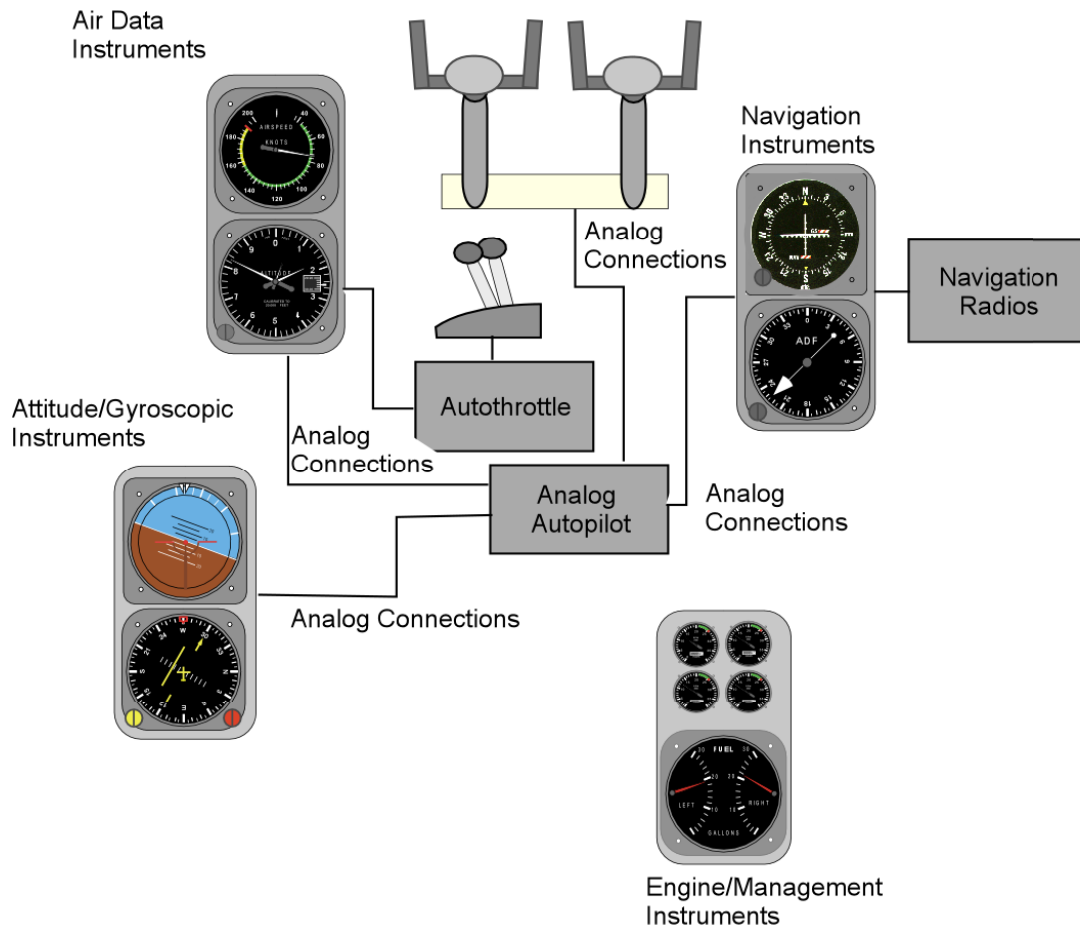
Figure 4.1. Schematic of Pre-FMS electromechanical flight deck

4.1.2 Electromechanical with FMS

The electromechanical flight deck with the inclusion of the FMS is represented in Figure 4.2. In this flight deck the FMS made its debut, interacting with various systems that previously were completely independent from one another. The FMS provided guidance commands to the auto flight system rather than having the auto flight system drive directly from the navigation instruments. The FMS also auto-tuned the navigation radios and made use of the inertial navigation system to accurately determine position. The FMS accessed the engine and fuel system data to estimate aircraft performance such as range and endurance. The rest of the cockpit remained unchanged. The pilots still used electromechanical 'steam gage' instruments. Interaction with the FMS was limited to the CDU. Most connections between hardware were analog, with the exception of the connection between the CDU and FMC which used the new ARINC 429 data bus.
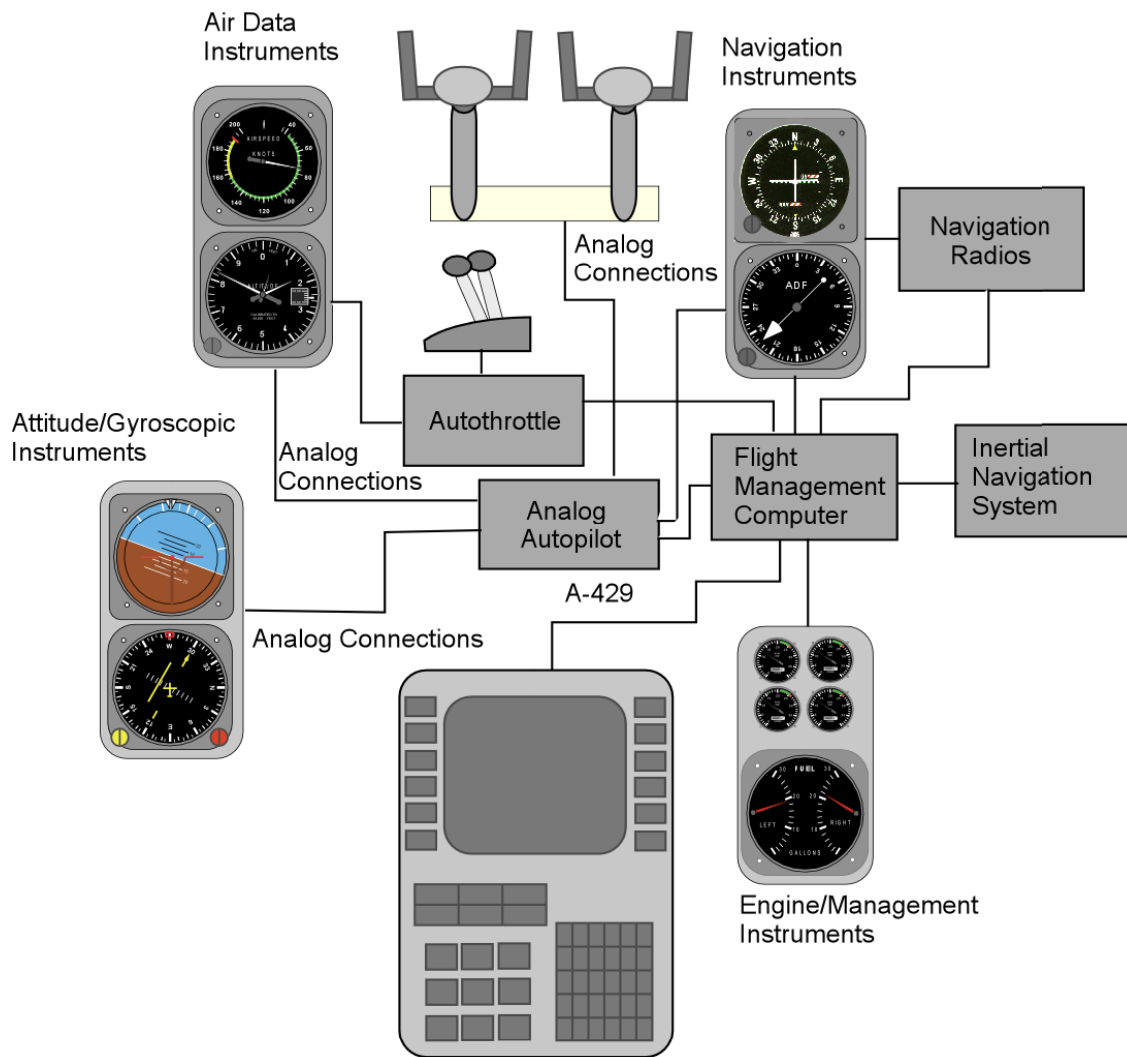
Figure 4.2. Electromechanical Flight deck with an FMS

4.1.3 Hybrid / EFIS with FMS

In the mid 1980s, as computer systems became more powerful, some of the original cockpit displays were replaced with electronic equivalents resulting in a hybrid flight deck that had digital avionics mixed in with the older analog systems. (See Figure 4.3.) These electronics instruments consisted of the Electronic HSI, which gave a graphical image of the route the FMS was using along with much other information that previously could not be viewed graphically.
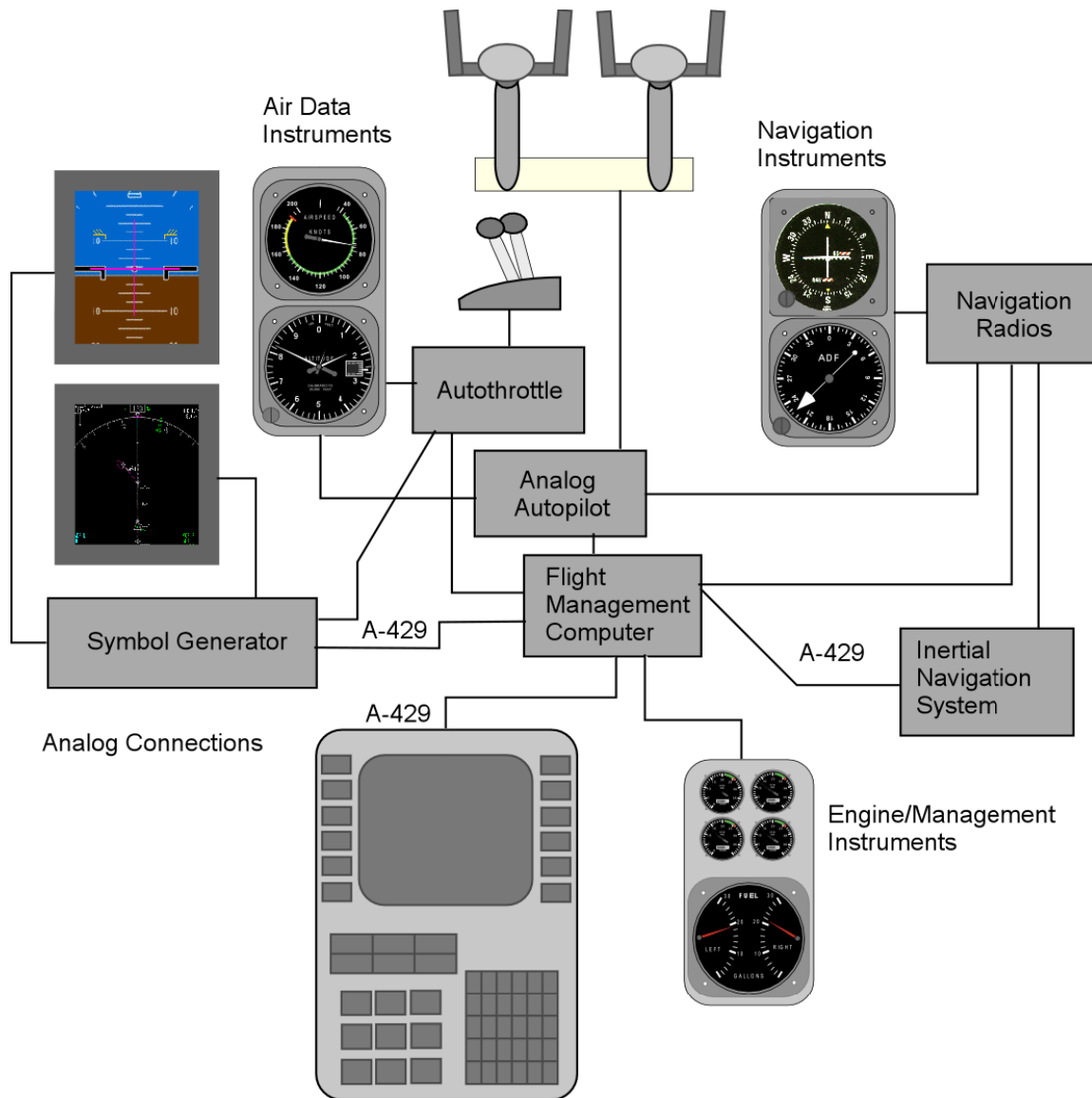
Figure 4.3. Hybrid EFIS flight deck circa 1988

Such information included the location of airports and navaids on a primitive moving map display. The attitude gyro was replaced with an electronic version that was driven by information obtained from the IRU/INS (Inertial Navigation System). A unit called a symbol generator was used to prepare the graphical images after the information was obtained across the ARINC 429 data bus. The new system was referred to as the EFIS, Electronic Flight Information System.

The system provided a much better representation of the route data than what had been provided previously and gave the pilot much better situational awareness. However, the electromechanical pitot-static instruments, such as airspeed, Mach, and altitude, were retained.

4.1.4 Full Digital Distributed Glass Cockpit

The current evolutionary step is the full digital, distributed, glass flight deck. All analog instruments and systems have been removed. The electronic attitude display was upgraded to include all air data (pitot-static) information in addition to attitude display and is referred to as the PFD, primary flight display. Additionally, the EICAS (Engine Instrument and Crew Alerting System) was added. The EICAS monitors system sensors and provides a high level synopsis of aircraft systems. In this system, all aircraft state information comes from the ADIRU (Air Data Inertial Reference Unit). The data exchange unit transfers information and provides the graphics for the displays. Digital autopilots and auto-throttles operate the aircraft while the FMS is still the center of flight operations. All data links are digital. Many distributed digital entities are sharing information through digital data link [SP00]. This is depicted in Figure 4.4.
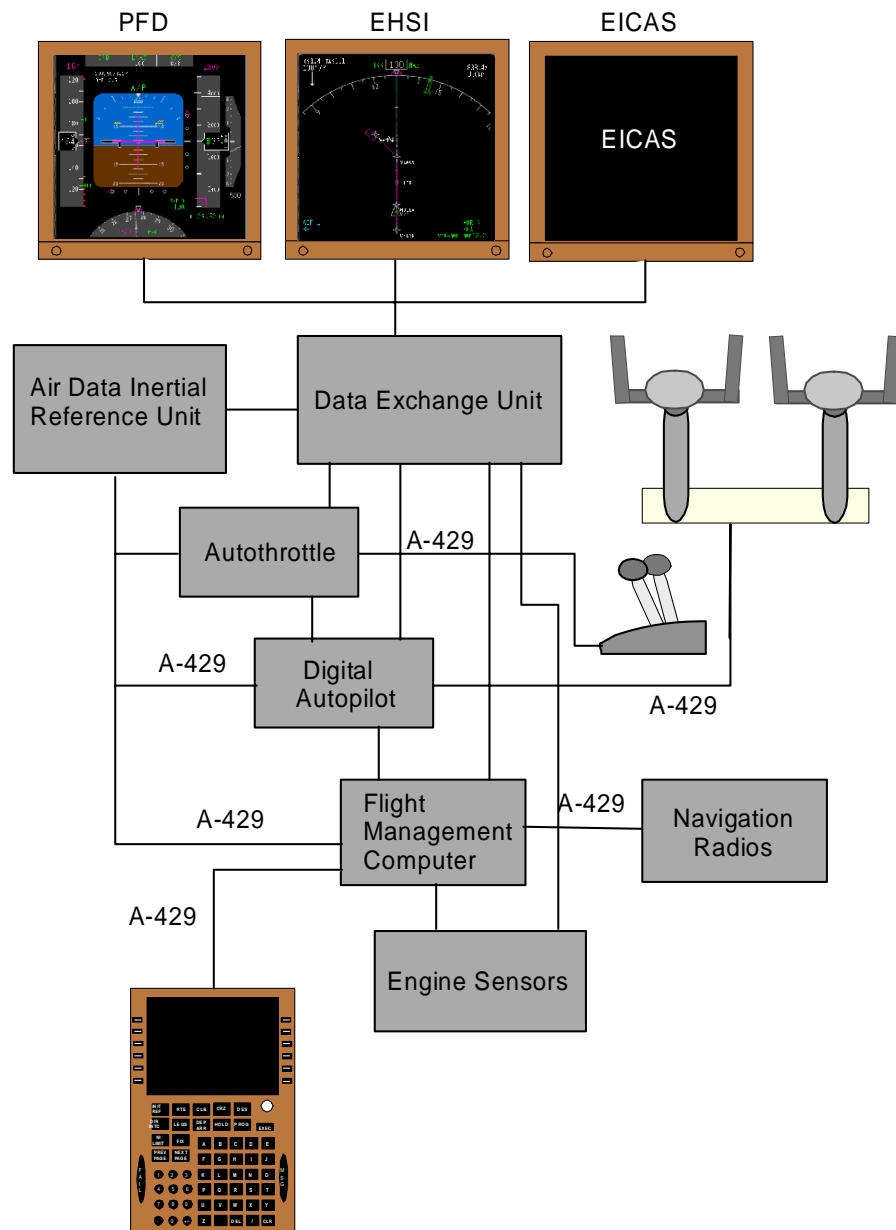
Figure 4.4. Fully Digital / Next Generation Flight Deck

4.1.5 Centralized Computing Architecture

The fifth phase of development, which currently represents state-of-the-art thinking in flight deck design, is the Centralized Computing Architecture. Avionics manufacturers have realized that weight and complexity could be reduced if all software processes could run on a centralized computing platform. This platform could conceivably host the major flight systems, such as FMS, auto-flight systems and the EICAS system, all on one platform. The advantage to this architecture is that all systems could share the same operating system, I/O features, and memory. Figure 4.5 represents a greatly simplified representation of such a system to emphasize the centralized nature of current thinking. From the pilot's perspective, there is little functionality change between the old and the distributed digital system [SP00].
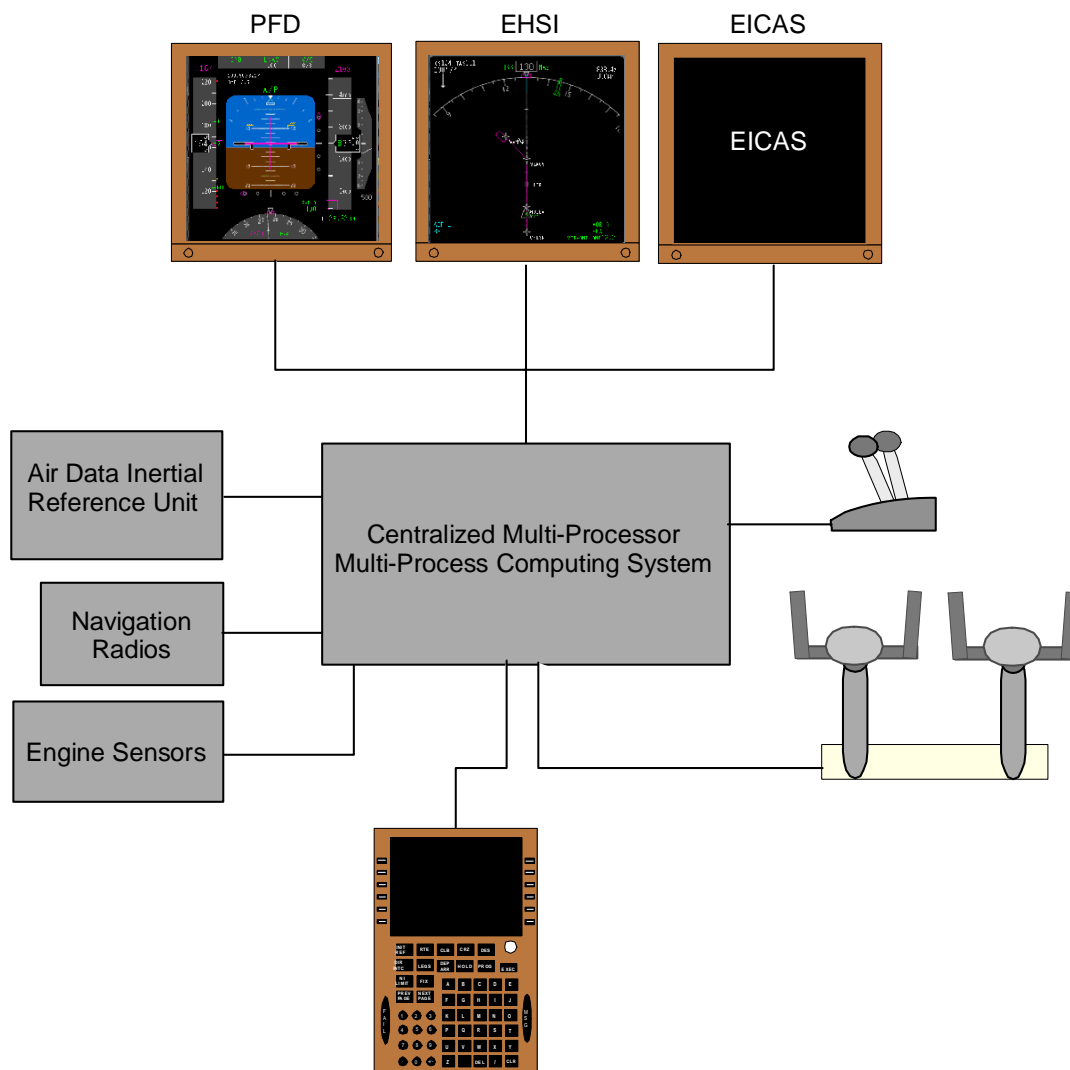
Figure 4.5. Centralized Computing Architecture

4.1.5.1   IMA architecture

The centralized architectures are often referred to as Integrated Modular Avionics (IMA). While there are various designs for IMA, they all share a basic theme of a number of avionics cabinets that are connected together. These include other peripheral equipment by means of a number of multiple-access serial data buses as shown in Figure 4.6. Each cabinet is seen as a high power computing module which replaces many, single-purpose Line Replaceable Units (LRU) [SP00].
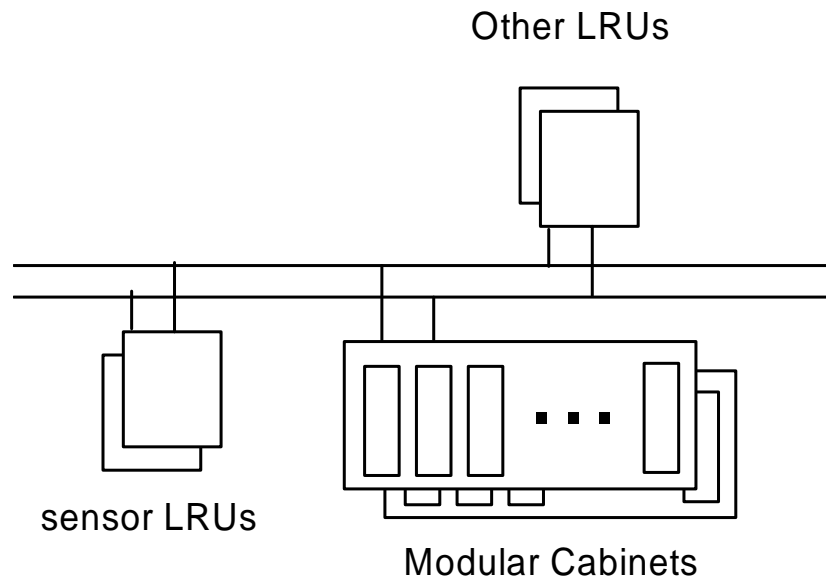
Figure 4.6. Simplified representation of Integrated Modular Avionics (IMA) architecture [SP00]

Each cabinet contains a selected mix of Line Replaceable Modules including core processors, power supplies, and I/O devices, along with other special LRMs.

4.1.5.2   ARINC specifications on IMA architecture

The IMA architectures are mature enough that ARINC has published several documents dealing with the hardware architecture and partitioning of the software processes. ARINC Report 651, "Design Guidance for Integrated Modular Avionics," is a top-level design guide for the design and implementation of modular avionics systems. ARINC Specification 653 is a result of specific requirements identified within ARINC Report 651. ARINC Report 652, "Guidance for Avionics Software Management," is a top-level design guide for managing the development and maintenance of avionics software. It provides guidance for the design and implementation of avionics software for traditional ARINC 700-Series equipment and Integrated Modular Avionics (IMA). ARINC Specification 629 defines a global data bus for a variety of aircraft systems. ARINC Specification 659 defines a controlled impedance backplane bus for Integrated Modular Avionics (IMA). [ARI97]

4.1.5.3   Software partitioning

The modular cabinet in an IMA system supports one or more avionics applications and allow independent execution of those applications. This can be correctly achieved if the system provides partitioning, i.e., a functional separation of the avionics applications, usually for fault containment (to prevent any partitioned function from causing a failure in another partitioned function) and ease of verification, validation and certification. The unit of partitioning is called a partition. A partition is basically the same as a program in a single application environment: it comprises data, its own context, configuration attributes, etc. For large applications, the concept of multiple partitions relating to a single application is recognized.

One method of creating the necessary software partitions is to create an APEX (APplication/EXecutive) interface between the Operating System (O/S) of an avionics computer resource and the application software. A basic sketch of the architecture is shown in Figure 4.7. The APEX interface, between the application software and the O/S, defines a set of facilities which the system will provide for application software to control the scheduling, communication, and status information of its internal processing elements. The APEX interface can be seen from the viewpoint of the application software as a high order language (HOL) specification and from the O/S viewpoint as a definition of parameters and entry mechanisms (e.g., trap calls). APEX may include a layer that translates from the HOL specification into the appropriate entry mechanism. This translation is directly dependent on the O/S implementation and hardware platform, and probably also on the compiler used for application software. If library routines are used, they may need to be included within the application code to preserve robust partitioning [ARI97].
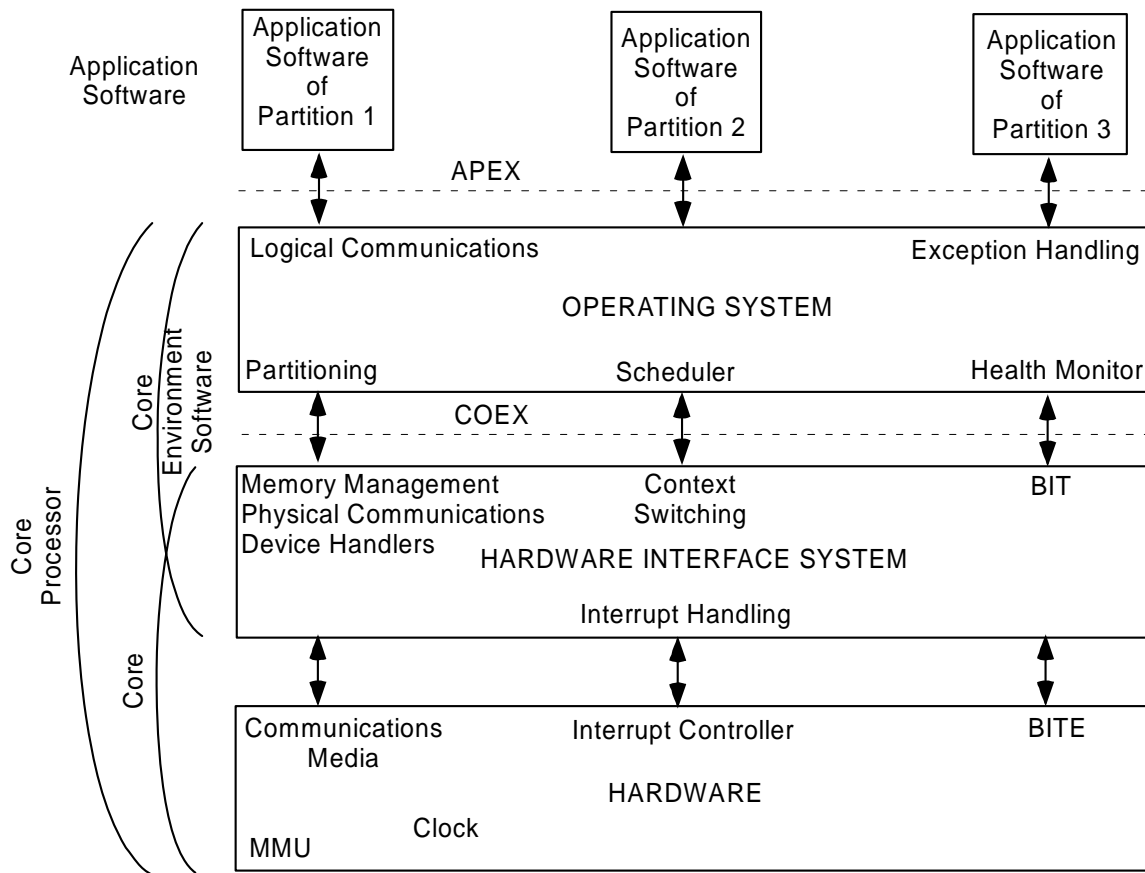
Figure 4.7. Software/Hardware partitioning architecture [ARI97]

5. Evolution of the Boeing 737 Flight Deck

To illustrate the progression of avionics development discussed in Section 4, we examine the actual flight deck evolution of the B-737. The B-737, the airliner Boeing has produced in the greatest quantities, provides the perfect illustration for the evolution from the 'classic' round dial flight deck through the fully digital glass cockpit. The final evolutionary phase of the centralized/IMA environment has not yet taken place on the B-737. For a real life example of a centralized architecture, we study the B-777 in Section 7.

In 1967, a small, short-range B737 twinjet airplane was conceived to complement the B707 and the B727. There was increasing demand for transports in its category, but the B737 faced heavy competition from the Douglas DC-9 and the British Aircraft Corp. BAC-111 [A04].

Figure 5.1. Original 737-100

At first, the B737 was called the "square" airplane because it was as long as it was wide. The new technology made the position of flight engineer redundant; the B737's two-person flight deck became standard among air carriers. Nineteen B737-200s, modified as T-43 navigator trainers, served with the Air Force, and the last B737-200 was delivered Aug. 8, 1988.

By 1987, the B737 was the most-ordered plane in commercial history. In January 1991, 2,887 B737s were on order and Models B737-300, -400 and -500 were in production. By 1993, customers had ordered 3,100 B737s, and Boeing was developing the Next-Generation B737s — the -600, -700, -800 and -900. The Next-Generation B737 models build on the strengths that made the B737 the world's most successful commercial airliner, while incorporating improvements designed for the 21st century.

The 126- to 149-seat B737-700 was launched in November 1993 and first delivered in December 1997. The 162- to 189-seat B737-800 was launched Sept. 5, 1994. The 110- to 132-passenger

B737-600 was first delivered in 1998, and the 177- to 189-passenger B737-900 was first delivered in 2001. [A04]

The B737 flight deck has progressed to its current state through three major evolutionary jumps; these are now discussed.

5.1 Classic B-737 Flight Deck

When the B-737 was first introduced, it was equipped with a flight deck similar to the flight deck shown in Figure 5.2. The cockpit was equipped with electro-mechanical pitot-static / gyro instruments that were coupled to analogue autopilots. Analogue navigation equipment and their associated displays (VOR/DME/RMI/HSI) provided navigation capabilities. Later versions were augmented with early Flight Management Computers and inertial reference systems.
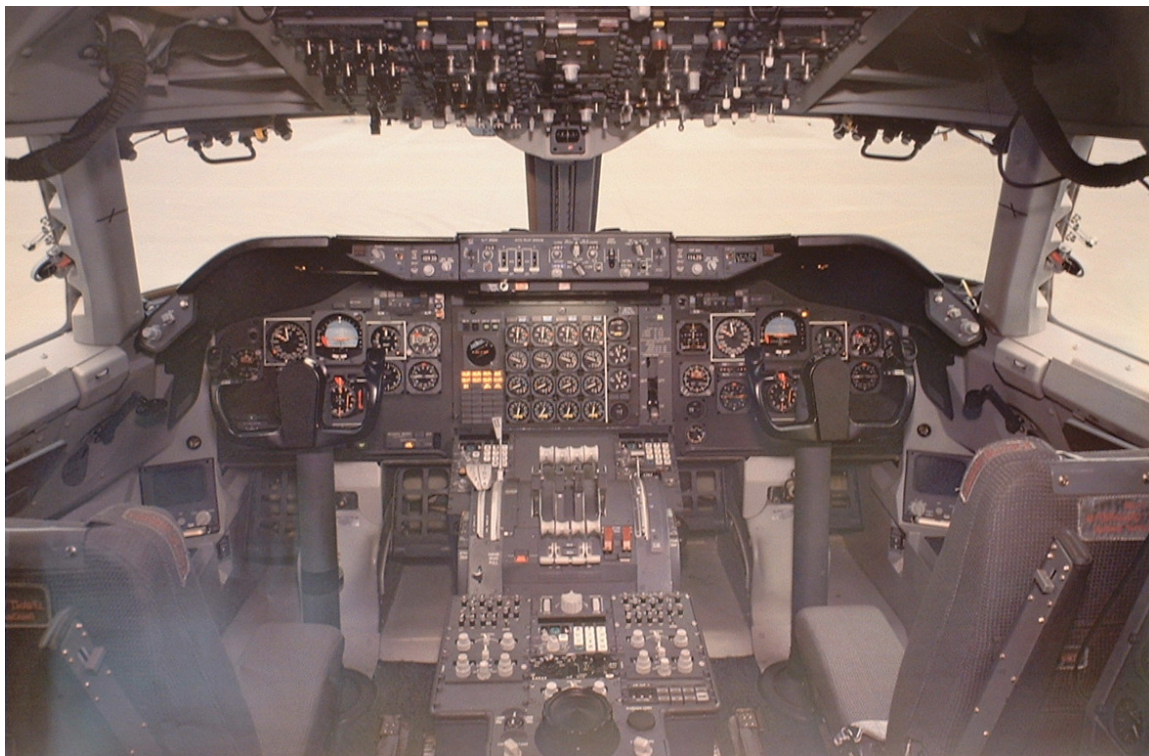
Figure 5.2. Typical classic Boeing flight deck

A schematic of the classic B-737 flight deck with FMC augmentation is shown in Figure 5.3. The flight deck major features consist of electromechanical flight instruments, full automatic flight control using dual flight control computers and an auto-throttle, and inertial reference systems for precise navigation. The aircraft also has a single Flight Management Computer controlled by dual CDUs [He98]. The components on the schematic are defined as follows:

- MCP: Mode Control Panel (Controls Autopilot);
- MASI: Mach Airspeed Indicator;
- ADI: Attitude/Direction Indicator;
- HSI: Horizontal Situation Indicator;
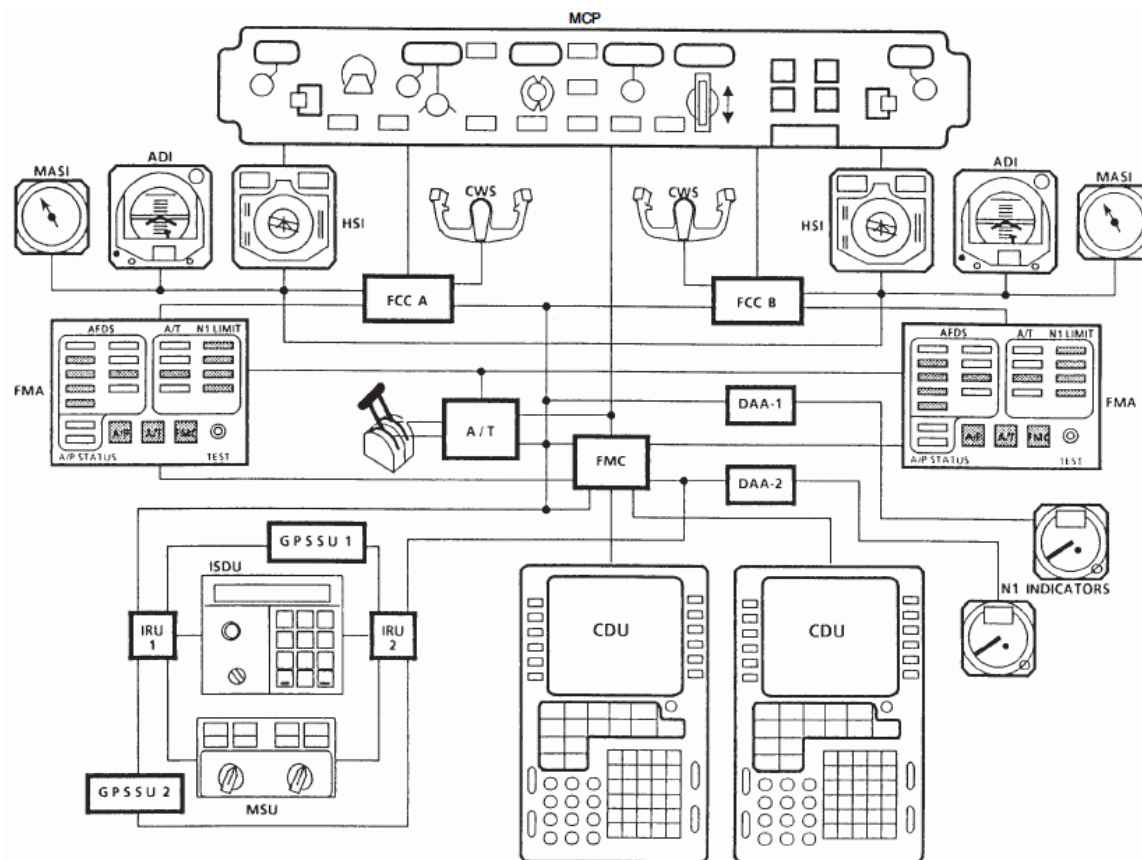
Figure 5.3. Classic electromechanical flight deck schematic for the B-737 (Courtesy Smiths Aerospace)

- CWS: Control wheel steering;
- FCC: Flight Control Computer;
- AFDS: Autopilot/Flight Director System;
- A/T: Auto-Throttle;
- FMC: Flight Management Computer;
- FMA: Flight Management Advisor;
- CDU: Control Display Unit;
- IRU: Inertial Reference Unit;
- ISDU: Inertial System Display Unit;
- GPSSU1: Global Positioning System Sensor Unit 1; and
- GPSSU2: Global Positioning System Sensor Unit 2.

Most of the connections between components are analog, with the exception of a few ARINC429 digital connections between the digital components, such as the CDU and the FMC. The classical mechanical flight deck, while having an antiquated appearance, is still quite capable of fully automatic flight control with an FMS. Certainly, the pilots are not provided with the level of

55

situational awareness that is possible with modern integrated displays, and information such as weather radar returns must be viewed on separate screens [He98].

5.2 EFIS Boeing Flight Deck

The next evolutionary step for the B-737 flight deck is the EFIS (Electronic Flight Information System) flight deck. The EFIS flight deck represents the intermediate step between the electromechanical flight deck and the complete digital glass cockpits. The flight deck replaced the mechanical attitude indicators and horizontal situation indicators with the Electronic HSI and the Electronic ADI, while retaining the mechanical pitot-static instruments to either side of the flight display (see Figure 5.4). On this flight deck, the Electronic HSI provides a much richer lateral picture to the pilot for increased situational awareness.

Figure 5.4. EFIS installation for later model B-737

The panel is also augmented with two center displays where the Engine Indication and Crew Alerting System (EICAS) displays are contained. A schematic drawing of the B-737 hybrid flight deck is shown in Figure 5.5. The main difference between the EFIS schematic and the classic schematic is seen in the presence of the EHSI and the Electronic Attitude and Direction Indicator (EADI), both of which are driven by the symbol generator. The symbol generator collects data from various sources through the ARINC 429 data bus and creates the graphical images for the displays. Data for the symbol generator come from the Flight Management Computer, the Flight Control Computers, and the auto-throttle [He98].

Figure 5.5. Classic EFIS flight deck schematic for the B-737 (Note: EICAS detail omitted) (Courtesy Smiths) Aerospace)

The components on the schematic are defined as follows:

- EHSI: Electronic Horizontal Situation Indicator;
- EADI: Electronic Attitude Direction Indicator;
- EIS: Electronic Instrument System;
- AA: Autopilot Annunciator;
- SG: Symbol Generator;
- ISDU: Inertial System Display Unit;
- MSU: Mode Select Unit; and
- IRU: Inertial Reference Unit.

5.3 Fully Digital, Distributed, B-737 Next Generation Flight Deck

The current phase of B-737 flight deck development, still referred to as the 'next generation' flight deck, employs the full digital glass cockpit as discussed previously in Section 2. A photo of this flight deck is shown in Figure 5.6. The photo shows the standard six flat-panel LCD displays that now dominate modern flight decks. The autopilot MCP is located on the glare shield, and two CDUs are located in the center console. Figure 5.7 shows the block diagram for this flight deck. The components on the schematic are defined as follows:

Figure 5.6. Photograph of next generation flight deck

- DU: Display Unit;
- CDU: Control Display Unit;
- MCP: Mode Control Panel;
- FMC: Flight Management Computer;
- FCC: Flight Control Computer;
- A/T: Auto-throttle;
- DEU: Data Exchange Unit;
- ADIRU: Air Data Inertial Reference Unit; and
- AA: Autopilot Annunciator.

The flight deck consists of six flat-panel displays that are driven by two Data Exchange units. Here the ADIRU provides all of the state information for driving displays, auto flight systems and the FMC. All of the single purpose electromechanical instruments have been removed. Detail regarding the inclusion of other avionics such as navigation radios and other sensors is omitted.

The 'Next Generation' Boeing 737 is equipped with Honeywell's all-digital flight control systems using advanced packaging techniques, combining fail-operational, fail-passive integrated flight director/autopilot systems with multiple sensor redundancy management. Through this technique, sensor data from both sides of the aircraft are available to flight guidance computers to provide monitoring, as well as continuous operation, after sensor failure. Similar systems also equip the McDonnell Douglas MD-80, MD-90 and MD-11 and BAE/Avro RJ series [S04].

The Boeing 737 is equipped with Smiths Aerospace's Flight Management Computer System (FMCS) integrating RNP, RNAV and Global Positioning capabilities. The FMCS incorporates advanced navigation performance and improved cockpit operations to take full advantage of state-of-the-art procedures.
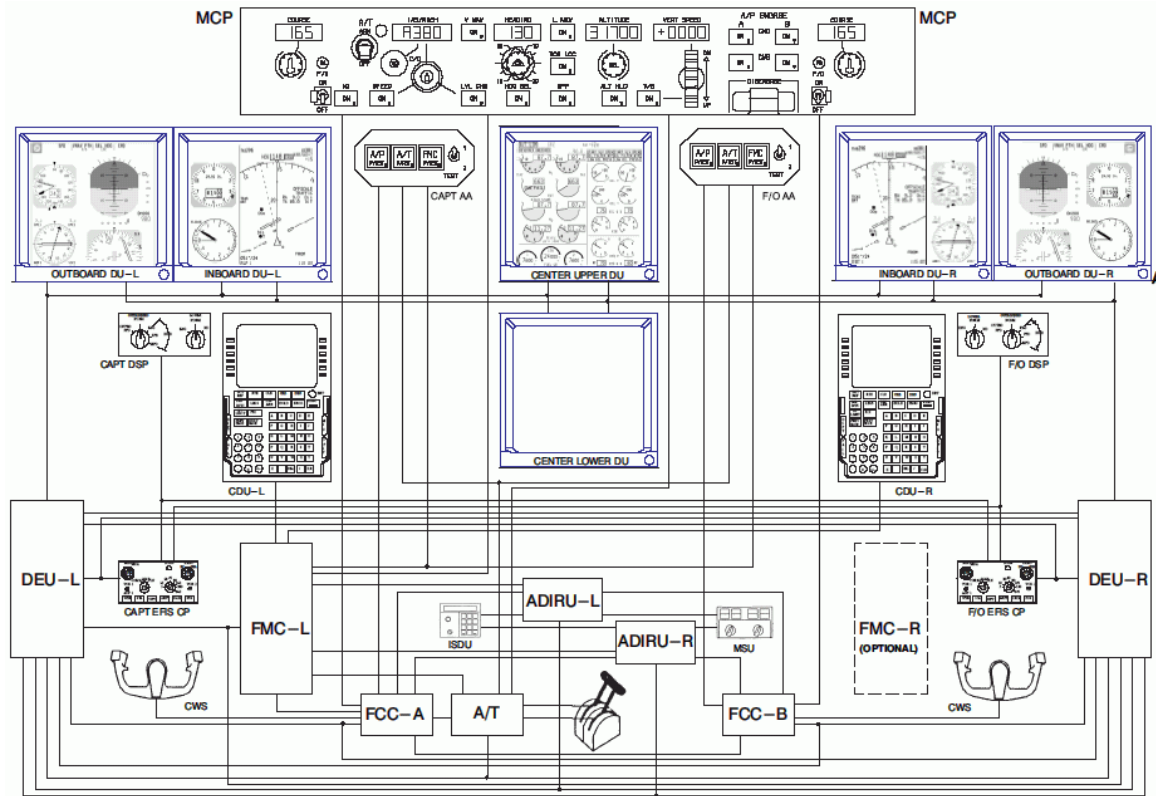
Figure 5.7. Next Generation flight deck for the B-737 employing a full glass cockpit (Courtesy Smiths Aerospace)

Accurate flight profile predictions for primary and alternate destinations are given for various performance options. This includes a required time of arrival (RTA) mode that controls the flight to arrive within six seconds at any point in flight. The Smiths FMS also comes equipped with the following features [S04]:

- Supplemental route storage and recall using the Jeppesen FliteStar® flight planning tool or through the Multipurpose Control Display Unit (MCDU);
- Backup navigation using the MCDU with GPS;
- Data link of flight plans and display of weather maps;
- Speed and altitude intervention using the glare-shield mode control panel;
- Automated uplink of predicted en route winds and ATC clearances; and
- Onboard worldwide navigation data base storage capability.

Adaptable data link allows an airline to customize their ACARS interface.

Some technical specifications for the FMS ((FMC) MODEL 2907A4) are as follows:

- 32 bit processor;
- Memory - 16 MBytes EEPROM, 2 Mbytes RAM;
- ARINC 429 - 32 inputs, 16 outputs;
- Discrete signals - 69 inputs, 6 outputs;
- ARINC 702S - 4 MCU;

- Weight: 16.2lb;
- Power: 30.4 watts, 117 VAC, 400 Hz;
- Cooling: passive; and
- DO-160C environmental standard.

6. McDonnell Douglas MD-11 Flight Deck

The MD-11 represents the quintessential example of the distributed digital architecture as described in Section 4.1.4. First introduced in 1990, the MD-11 flight deck was the first of its kind and represented the culmination of flight deck integration concepts and ideas conceived in the 1980s. At the time it was the standard to beat. In most respects, it still is, although developments in some areas such as flat-panel displays have gone beyond the 1990s technology of the MD-11. The MD-11 is important to study because it defined the nature of flight deck automation, and most modern flight decks mirror its architecture and functionality [SP00].

The MD-11 is a derivative of the DC-10 airframe (see Figure 6.1) with an entirely new avionics system. One major advantage of the MD-11 is that it is operated with a two pilot crew while the DC-10s required a third crewmember, the flight engineer, to manage all of the complex systems. A photograph of the MD-11 flight deck is shown in Figure 6.2.

Six 8-inch color displays provide the crew with aircraft flight and systems system information. The navigation system is based on redundant triple Inertial Reference Systems (IRS), dual Flight Management Systems (FMS), and an Automatic Flight System (AFS) based on dual Flight Control Computers (FCC). The system provides complete autonomous control including auto-throttle and autopilot control over the entire vehicle flight envelope. Category IIIb automatic landing (auto-land) capability is also provided. All systems that once were performed by a flight engineer, including hydraulic, fuel, electrical, and environmental settings, are now automated [SP00].

Figure 6.1. MD-11 with Delta Airlines markings

Figure 6.2. MD-11 flight deck

6.1   Navigation Systems

The navigation system for the MD-11 is built around a triple IRS and a dual FMS. A simplified schematic of the MD-11 navigation system is shown in Figure 6.3. The schematic shows a distributed digital architecture where the FMC and MCDU are linked by data bus to other avionics components. The FMC connects to the IRU, all navigation radios (GPS, VOR, DME, ADF, ILS), weather RADAR, and ACARS [SP00].

The FMS is the heart of the aircraft's navigation system and provides a number of functions that are central to operation of the airplane:

- Ability to create flight plans, including airways, SIDs, and STARs, by keyboard entry or data link;

- Multi-sensor navigation using inertial reference data, together with inputs from GPS, DMW, VOR, and ILS;

- Performance predictions for the complete flight plan, including altitude, speed, time of arrival, and fuel state;
- Guidance to the flight plan in three dimensions and controlling arrival time;
- Take-off and approach speed generation; and
- Providing VOR beam guidance mode.

Section 3 details the complete functionality of the FMS.
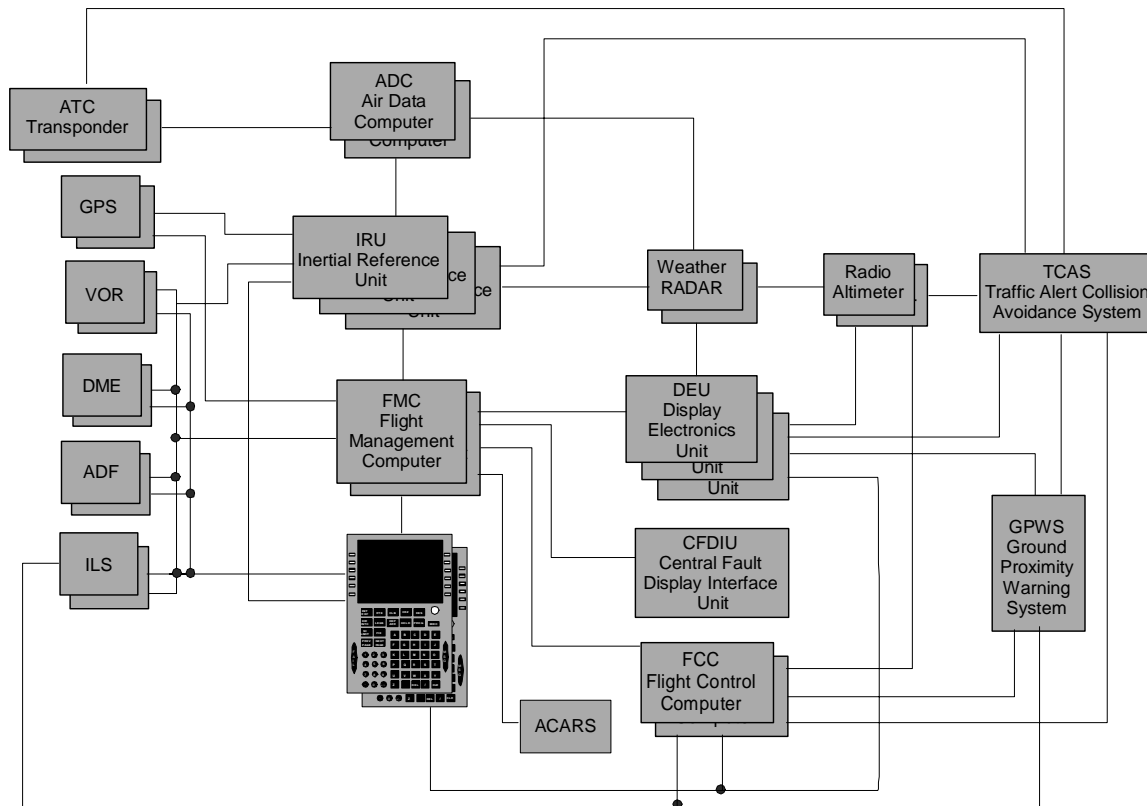
Figure 6.3. MD-11 navigation system architecture

The additional redundancy on the MD-11 goes beyond the need for safety of flight. The MD-11 needs to be able to dispatch with passengers on board even when some systems are not functioning. Since the MD-11 is a long-range aircraft, it is operated in regions where maintenance facilities may be thousands of miles away. Therefore the MD-11 has a triple redundancy navigation system. Additionally, a standby navigation system is provided in the MCDU, thus allowing for an FMC failure [SP00].

The Inertial Reference System provides a good independent position solution for short-term operation, or even for long-term operation within its capability of a drift up to 2 nmi/hr. However, to provide the accuracy necessary for the area navigation required in a modern airspace system or for terminal area operations, radio updating is necessary. This is provided on the MD-11 by having GPS, dual VOR receivers and dual DME transceivers. Automatic Direction Finding (ADF) is included for flying non-precision approaches and ILS approaches.

A dual air data system is also installed to provide airspeed altitude, etc, for display to the crew and as inputs for the other systems (AFS, FMS, etc.) that need such data.

Additionally, dual weather radar systems (with a single flat plate antenna) are provided, together with radio altimeters, ATC transponders, and Traffic Alert and Collision Avoidance Systems (TCAS). The weather radar is now capable of detecting wind shear ahead of the airplane. TCAS is a requirement for US operators and foreign operators flying in US airspace. Freighter aircraft are not required to have TCAS [SP00].

6.2 Flight Controls

The MD-11 airplane has a mechanical flight control system with stability augmentation provided by the flight control computers (FCC) and with irreversible, hydraulically-powered actuators. Its schematic is shown in Figure 6.4. The MD-11 has a conventional flight control column and rudder pedal configuration for the captain and first officer. The primary flight control system comprises the inboard and outboard elevators, the inboard and outboard ailerons, and one upper and one lower rudder. The secondary flight control system comprises the inboard and outboard wing flaps and slats, the wing spoilers/speed brakes, and a controllable horizontal stabilizer.

All primary and secondary flight control surfaces are hydraulically powered by two aircraft hydraulic systems. Flight control positions are displayed, normally by (Display Unit) DU 4, on the System Display (SD) by selecting the configuration page with the CONFIG cue switch on the System Display Control Panel (SDCP). In addition to the SD, flap and slat positions are also shown on the PFD. Alerts will appear on the Engine and Alert Display (EAD) and the SD.

Other than the slats, which are electrically controlled and hydraulically actuated, the flight control system is designed with a direct mechanical/hydraulic interface consisting of cables that run between the cockpit controls and the various hydraulic actuators that move the control surfaces. Therefore, with the exception of the slats, the movement of the control surfaces does not depend on the availability of electric power [BBMFGK96].

Three Pratt & Whitney (Palm Beach, Florida) PW4460 high-bypass ratio turbofan engines in the 60,000-lb thrust class power the MD-11 airplane. Two engines are mounted in underwing pods. The third engine is located at the base of the vertical stabilizer. Each engine has a full-authority digital engine control (FADEC) system in which the software was modified for the PCA program. The modification allows for an increased range of engine pressure ratio (EPR) commands to be sent from the FCC. The crew controls the engines with electronic throttles which command a power setting based on EPR [BBMFGK96].

A four-channel (dual-dual) auto flight system (AFS) is installed in the MD-11 providing autopilot and auto-throttle capabilities. The FCCs are built by Honeywell, Inc., Phoenix, Arizona, and operate at 20 samples /sec. The functions of the auto flight system include:

- Flight Director (FD)
- Auto-throttle
- Autopilot
- Autoland (Cat III)
- Yaw damper
- Auto stabilizer trim

- Stall warning
- Wind shear detection
- Elevator load feel
- Flap limiter
- Automatic ground spoilers
- Altitude Alerting
- Longitudinal stability augmentation
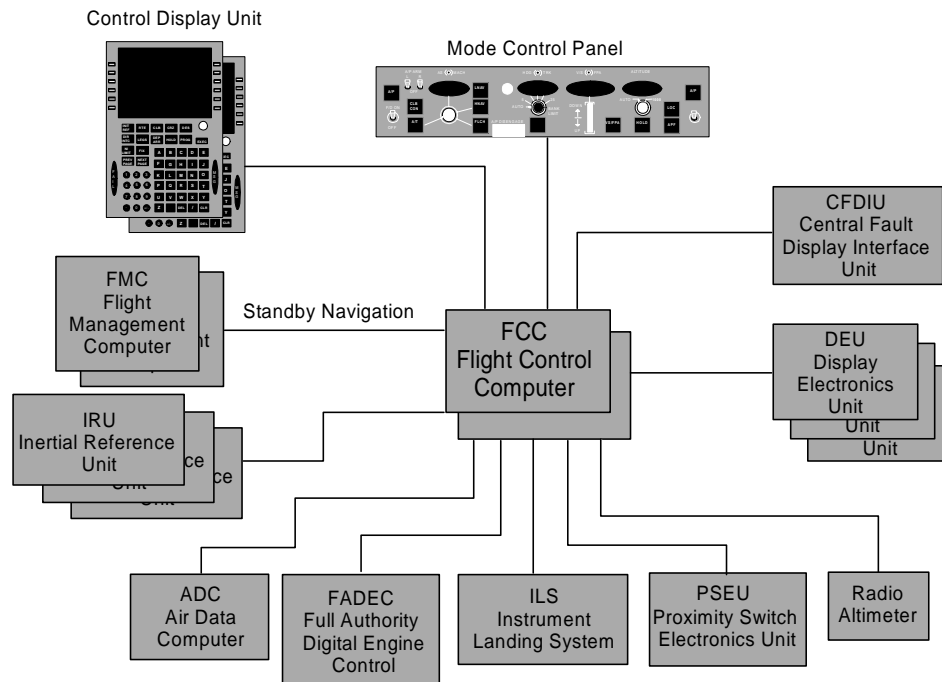
Figure 6.4. MD-11 Flight Control Computer interactions with other aircraft systems

The system architecture of the AFS is built around dual flight control computers (FCC) and the Mode Control Panel (MCP). The aircraft's auto-flight system is controlled directly through the MCP. The MCP controls the autopilot, the auto-throttle, and flight director. When the autopilot is engaged, the pilot can control the heading, vertical speed, and altitude of the aircraft directly through the MCP. When the auto-throttle is engaged, the speed of the aircraft can be controlled as well. Additionally, the autopilot can be controlled directly by the flight management system using LNAV and VNAV functions [SP00].

The MD-11 incorporates a longitudinal stability augmentation system (LSAS) that enhances longitudinal stability through commands to the elevators in a series mode. The LSAS holds the existing pitch attitude of the aircraft whenever the sum of the captain's and first officer's column forces is less than two pounds. In the software version that was installed in the occurrence aircraft, below 15,000 feet, there is no LSAS input when the column force is above two pounds. Above 15,000 feet, the LSAS provides an additional pitch rate damping input when the control column force is above two pounds. Automatic pitch trim of the horizontal stabilizer is also

operative in the LSAS mode. The MD-11 uses a yaw damper for lateral control augmentation [SR98].

The LSAS is inoperative whenever the autopilot is engaged or when the aircraft is below 100 feet above ground level (AGL). With the LSAS inoperative and automatic pitch trim unavailable, manual pitch trim is available [SR98].

The dual-dual FCC architecture is designed around the fail-operational Cat IIIb autoland requirement. Each FCC (see Figure 6.5) has two independent computational lanes to provide added integrity and redundancy. Each of these lanes consists of a power supply, two dissimilar microcomputers with dissimilar software, and servo-electronics to drive the actuators that move the aircraft's control surfaces. This triple dissimilarity is intended to limit the possibility of software errors in one lane resulting in unsafe operation. This architecture is used for the functions that require high integrity such as autoland. Functions that have lower criticality only use a single version and are spread across the different processors. The system is designed to allow the airplane to be dispatch with only one FCC operational; however, it would not be able to perform Cat IIIb autoland functionality [SR98].

An important element of the flight control system design is the need to provide appropriate levels of redundancy in the interfaces to the actuators for the flight control surfaces. A number of related issues have to be considered. These are:

- Dispatch with one FCC operating or one lane inoperative;
- Protection against both random and generic hardware and software failures; and
- Minimize the probability of multi-axis hard over failure.

Figure 6.5 shows how the elevator, aileron and rudder actuators interface to the various channels of the FCC to satisfy these requirements. The control surfaces are also interconnected mechanically, so driving only one elevator, for example, will actually result in all elevator panels moving. Sufficient control authority is retained in the event of loss of a single channel or even of a complete FCC. The diagram does not show the stabilizer control or the spoilers, which are driven by the aileron/spoiler mechanical mixers and are thus driven indirectly by the aileron actuators [SP00].

6.3 Aircraft Systems

One major goal of redesigning the DC-10 to become the MD-11 was to convert the three-crew flight deck of the DC-10 to a two-pilot flight deck, which is the current standard for the industry. To enable the MD-11 to be flown by a two-pilot crew, the Flight Engineer's role needed to be automated. The Flight Engineer managed the aircraft systems, including normal, abnormal, and emergency systems. This automation was made possible by advances in system control technology then enabled automatic execution of proven DC-10 procedures without excessive redesign of the system or procedures [SP00].

6.3.1 Aircraft System Controllers

The aircraft systems are monitored for proper operation by the Automatic Systems Controllers (ASC). In most cases, system reconfiguration as a result of a malfunction is automatic, with manual input being required for irreversible actions, such as engine shutdown, fuel dumping, fire agent discharge, or generator disconnect. A 'Dark Cockpit' philosophy is adopted in that during

normal operations all annunciators on the overhead panel will be extinguished, this confirming to the crew that all systems are operating normally and are properly configured.
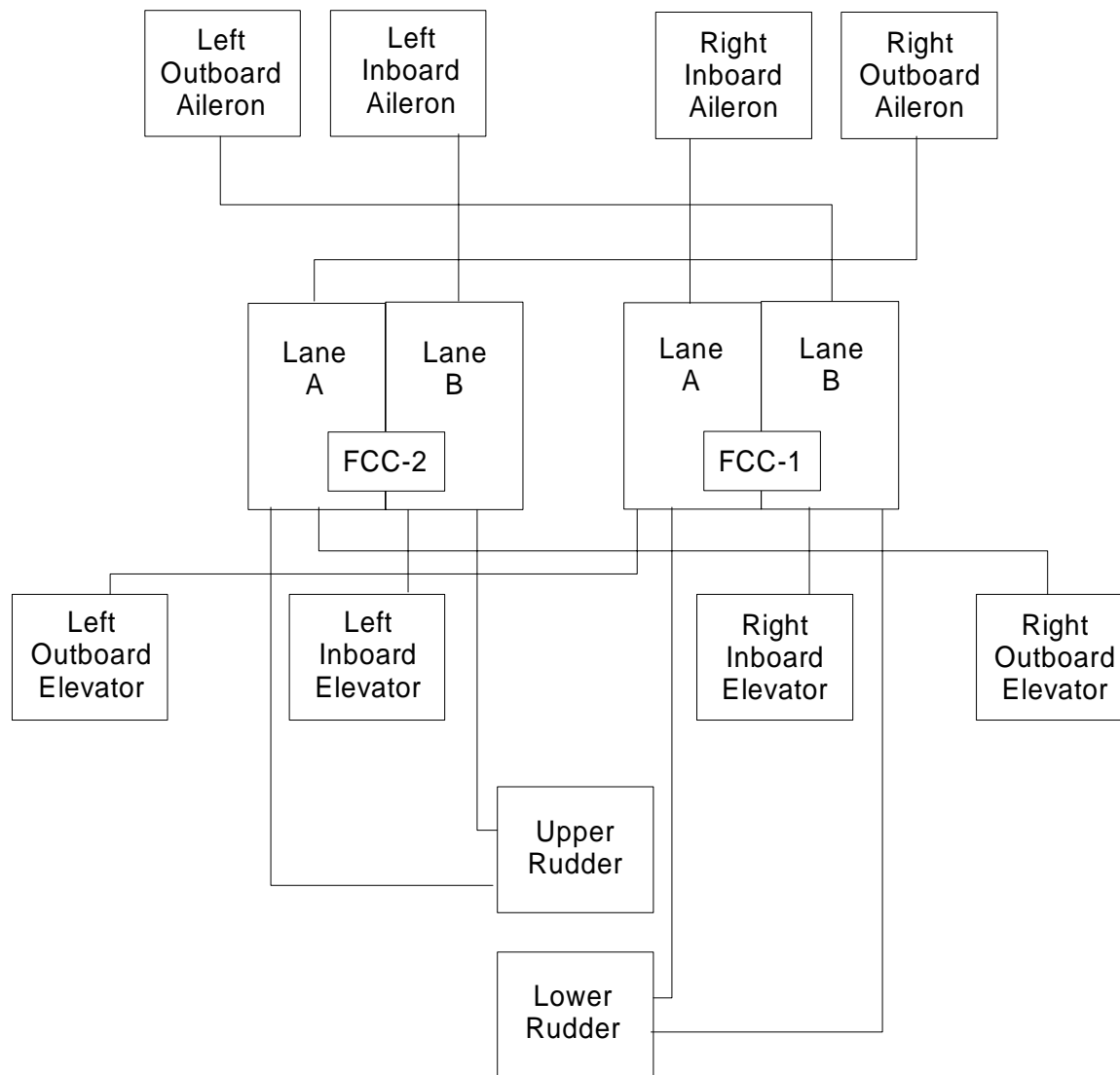
Figure 6.5. Auto Flight System actuator architecture

The MD-11 aircraft systems can be controlled manually from the overhead panel area of the cockpit. The center portion of the overhead panel is composed of the primary aircraft system panels, including Air, Fuel, Electric, and Hydraulic Systems, and is easily accessible by either pilot. Each panel is designed so that the left portion controls system #1, the center portion system #2, and the right hand portion #3.

Each Aircraft System Controller (ASC) has two automatic channels and a manual mode. If the operating automatic channel fails or is shut off by its protection devices, the ASC will automatically select the alternate automatic channel and continue to operate normally. If both automatic channels fail, the controller reverts to manual operation. The crew would then employ

simplified manual procedures for the remainder of the flight. To allow operators to maximize the dispatch reliability of the airplane, the MD-11 is certified for dispatch with up to two systems operating in manual mode. The general architecture for Aircraft Systems Controllers is shown in Figure 6.6.
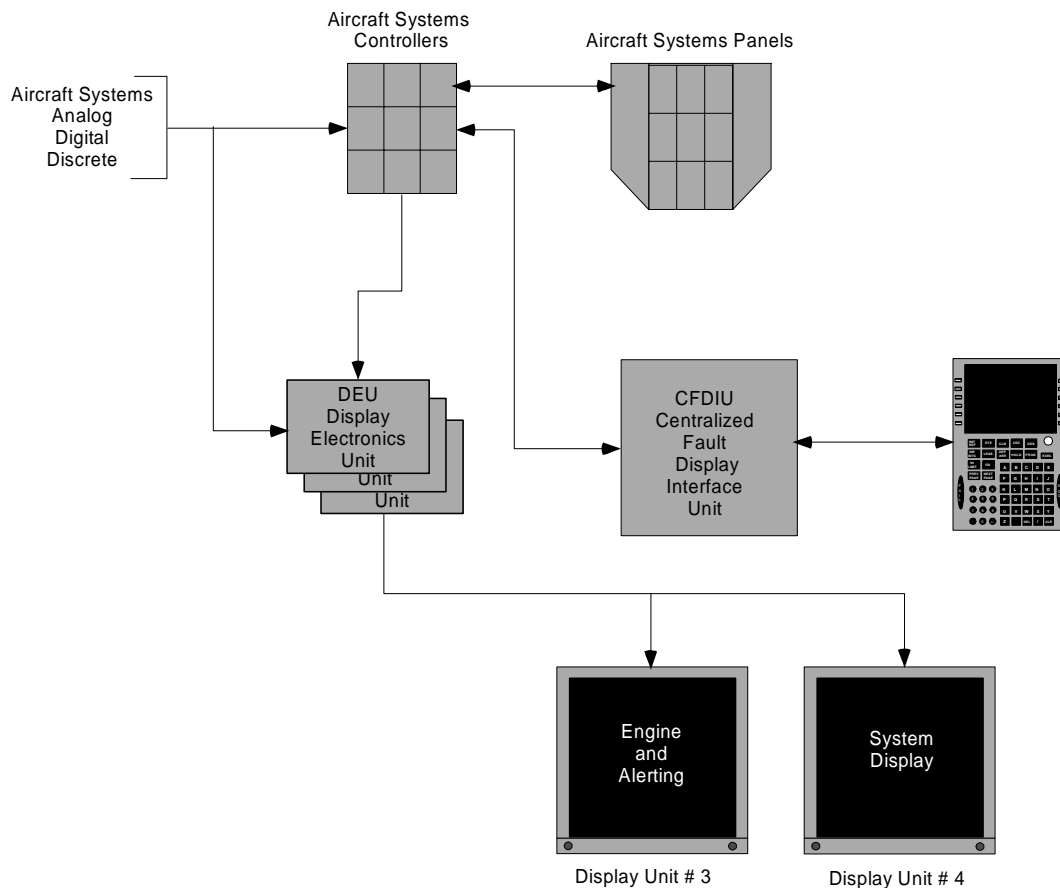
Figure 6.6. Generalized Architecture for Aircraft System Controllers (ASC)

The status of the aircraft and its systems are provided to the crew on the Engine and Alert Display (EAD) and the System Display (SD) using display units #3 and #4. These are equivalent to the EICAS system on the Boeing aircraft. Under normal operation, there is no need to review the overhead panels, which provide backup annunciation and manual interface only [SP00].

6.3.2 Maintenance Systems

The maintenance system on the MD-11 consists of two main elements, the Centralized Fault Display System (CFDS) that is standard on the airplane, and the On-board Maintenance Terminal (OMT) which is available as a customer option.

The CFDS consists of a Centralized Fault Display Interface Unit (CFDIU) and any of the three MCDUs, with the capability to interface to all the major avionics subsystems on the aircraft as shown in Figure 6.7. The functions provided by the CFDS are as follows:

- A summary of Line Replaceable Units (LRUs) that have reported faults on the last flight;
- Capability to select individual "Reporting LRU's" for review of current faults and fault history;

- Initiation of Return-to-Service testing of aircraft components (on-ground duty);
- Capability to view sensor data;
- Erasure of LRU maintenance memory (on-ground) only; and
- Ability to declare components inoperative for the Aircraft System Controllers (ASC).

The CFDS can also interface to an ACARS Management Unit to transmit fault data to the ground and to a printer on board the airplane.

The optional On-board Maintenance Terminal (OMT), shown in Figure 6.7, expands the capability of the CFDS and automates many of the required maintenance tasks. It contains a fault message database, which allows it to correlate each fault message to a specific flight deck effect. The displays on the OMT are customized by the individual airlines, but a typical display can show which LRU is involved, the fault message, the flight deck effect and alert, the Minimum Equipment List (MEL), documentation reference, and other useful information.

The OMT also incorporates a mass storage device, allowing it to store the aircraft maintenance document, including the aircraft Maintenance Manual (AMM), Fault Isolation Manual (FIM), MEL, Wiring Diagrams, etc. The built-in reference to this documentation allows these data to be provided automatically as part of the fault-tracing process [SP00].
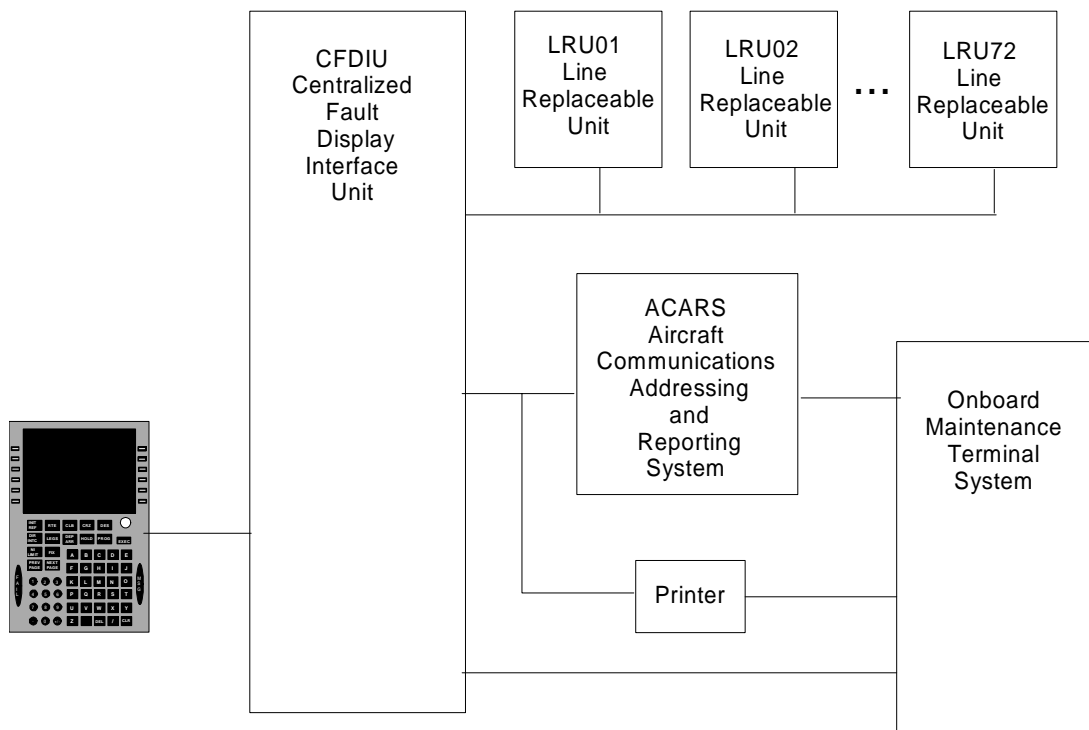
Figure 6.7. MD-11 maintenance system architecture

6.4   CNS/ATM Architecture

Classically, the principal domestic pilot/controller communications are via VHF radio. More recently the CNS/ATM data link that has become operational is the Aircraft Communication Addressing and Reporting System (ACARS) data link. The ACARS data link ground system is run by ARINC and operates as a service principally to the airlines. This beginning application was on the Boeing 747-400 FANS-1 package in the South Pacific.

The MD-11 was developed just before the CNS/ATM development became prominent. The existing flight management computer was designed to provide sufficient capabilities for the features required at the time of the MD-11's entry into service in 1990. It could probably provide sufficient computational resources to allow inclusion of the FANS-1 functionality, but most likely with some degradation of response time. However, growth in this configuration would be very limited [SP00].

7. Boeing 777 Flight Deck

The Boeing 777 flight deck represents a major advance in flight deck development for two reasons. First, its flight control system is a full fly-by-wire flight control system as opposed to the older mechanical hydraulic system. Secondly, it has started to take advantage of the benefits of the centralized computing architecture as discussed in Section 4.

While the MD-11 flight deck is quite capable and still represents the industry standard, it does not take advantage of substantial cost benefits that can be obtained from large-scale integrated computing. The MD-11 systems are made up of self-contained Line Replaceable Units (LRU) connected through ARINC 429 data buses. In this distributed architecture, each separate unit effectively duplicates hardware and software resources because of its need to be free-standing. The avionics industry has long recognized that substantial cost benefits could be realized if the various systems could share a large-scale computing architecture. Since the late 1980's, the avionics industry has worked on requirements for the next generation Integrated Modular Avionics (IMA) that are documented in ARINC 651. The Boeing 777 and its Aircraft Information Management System (AIMS) architecture represent the first application of an integrated computing architecture in a commercial air transport [SP00].

7.1   Boeing 777 System Architecture

The Boeing 777 system architecture makes use of the ARINC 629 data bus to connect all of the various systems as shown in Figure 7.1. The architecture consists of a triple redundant flight control system and a triple redundant auto flight system. There are dual Air Data Inertial Reference Units as well. Other non-flight systems are connected through A629, also. In the center of the architecture are dual AIMS cabinets that represent the major step towards centralized computing architecture [U02].

7.2   Boeing 777 Airplane Information Management System (AIMS)

The Boeing 777 Airplane Information Management System (AIMS) implements the IMA concept in an architecture that supports a high degree of functional integration and reduces duplicated resources. The conventional LRUs of the MD-11 vintage aircraft are replaced with dual integrated cabinets which provide the processing power and input/output (I/O) hardware and software required for the following functions:

- Flight Management (FMS);
- Displays;
- Central Maintenance;
- Airplane Condition Monitoring;
- Communication Management and Flight Deck Communication; and
- Data Conversion (ARINC 429 / 629 data bus conversion).

The integrated cabinets are connected to the airplane interfaces via a combination of ARINC 429, ARINC 629 and discrete I/O channels. Figure 7.2 provides a detail of the processes contained in the AIMS cabinet. [U02]
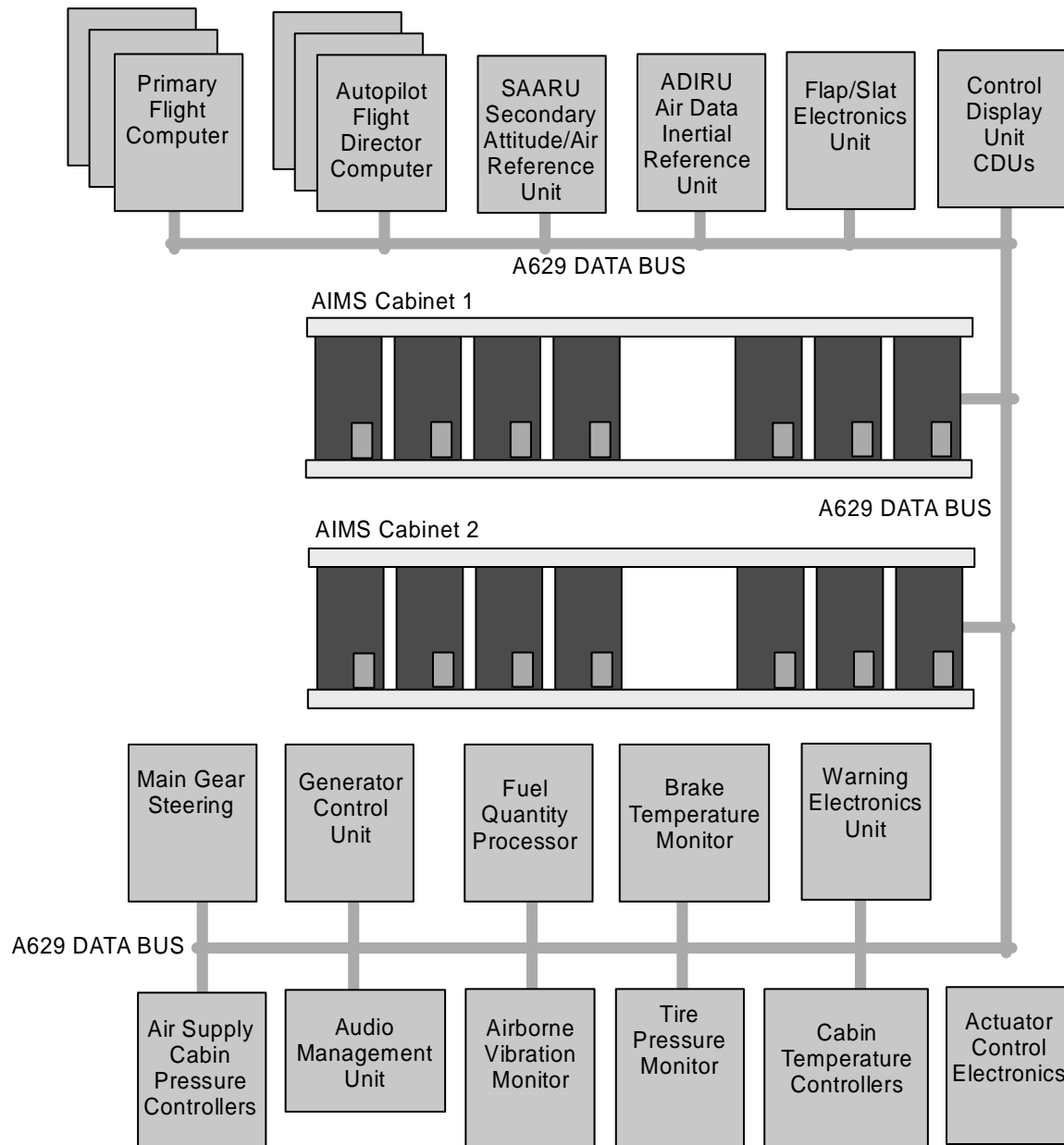
Figure 7.1. Boeing 777 System Architecture [U02]
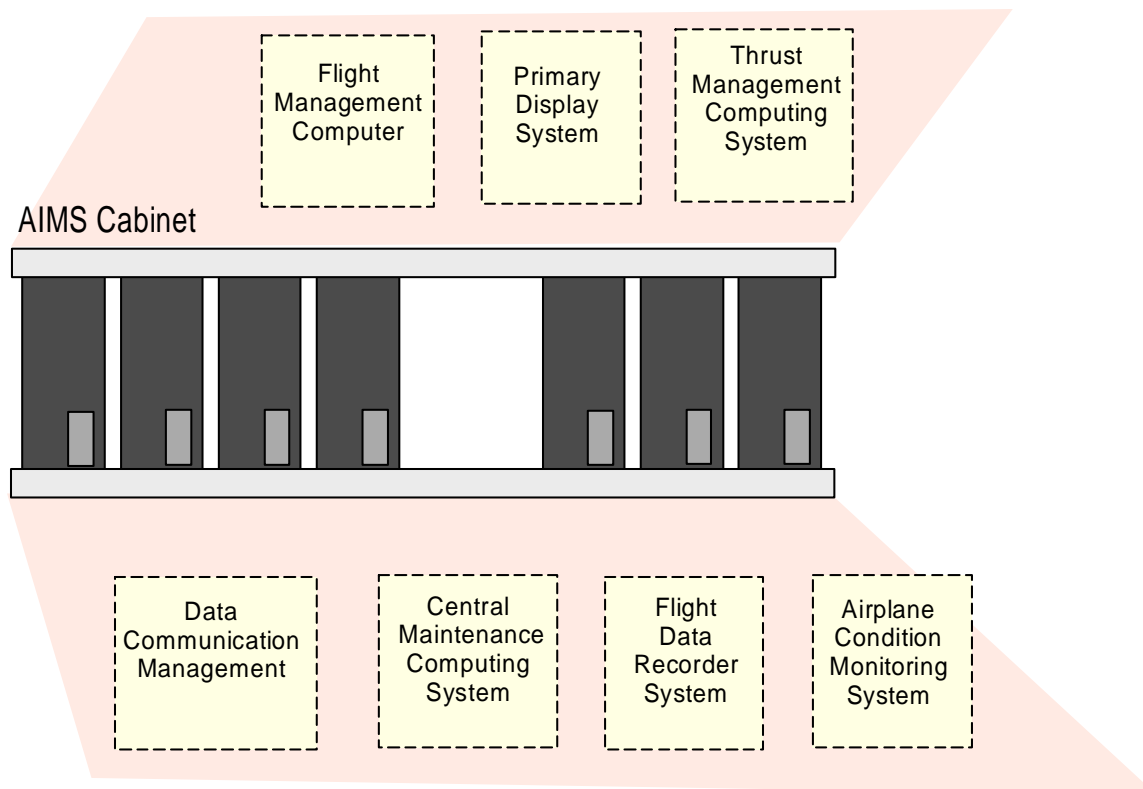
Figure 7.2. B777 AIMS System Architecture [U02]

The AIMS system consists of dual cabinets in the electronics bay; they each contain four core processor modules (CPM) and four input/output modules (IOM), with space reserved in the cabinet to add one CPM, and two IOMs to accommodate future growth. The shared platform resources provided by AIMs are:

- Common processor and mechanical housing;
- Common I/O ports, power supply, and mechanical housing;
- Common backplane bus (SAFEbus TM) to move data between CPMs and between CPMs and IOMs; and
- Common operating system and built-in test (BIT) and utility software.

Instead of individual applications residing in a separate LRU, applications are integrated on common CPMs. The IOMs transmit data from the CPMs to other systems on the airplane and receive data from these other systems for use by the CPM applications. A high-speed backplane bus, called SAFEbus, provides a 60Mbits/sec link between any of the CPMs and IOMs in a cabinet. Communications between AIMS cabinets is through four ARINC 629 serial buses.

AIMS core processing modules (CPMs) come in four basic flavors. Each type has a common set of processing resources — processor, instruction memory, bus interfaces and power — and some unique circuit card assemblies (CCAs), or plug-in modules. The CPMs include:

- CPM/Basic, which does not have a special-function CCA;

- CPM/Comm, with interfaces to the airplane fiber optic LAN (local area network), the A717 interface to the flight data recorder, and an RS-422 interface to the quick access recorder;

- CPM/GG (graphic generator), with the core processor and a graphic generation CCA, which connects to the flight deck display units; and

- And CPM/ACMF (aircraft condition monitoring function) with an additional memory CCA that stores ACMF data.

Because the AIMS architecture uses generic building blocks, a need existed for multiple software applications to be able to share common hardware resources, without corrupting each other's data. This led to the development of Honeywell's Apex operating system — with its time and space partitioning — which became the foundation for the ARINC 653 operating system spec. Under Apex, for example, the central maintenance function (Level D of DO-178B), flight deck communications (Level C) and DCG (Level A) can share the same processing hardware yet still be developed and verified independently. This is achieved through judicious memory management and deterministic scheduling of application software execution. Memory is allocated before run time, and only one application partition is given write-access to any given page of memory. Scheduling of processor resources of each application is also done before run time and is controlled by a set of tables. These tables are loaded onto each CPM and IPM in the cabinet and operate synchronously, and controlling the application scheduling on the CPMs as well as data movement between modules across the SAFEbus [A03].

Hardware fault detection and isolation is achieved via a lock-step design of the CPMs, IOMs, and the SAFEbus. Lockstep processing means that dual, self-checking processor pairs constantly check the accuracy of operating functions and are able to detect and instantaneously create "containment zones" around a faulty processor module, so that a fault is not propagated throughout the system. Lockstep processing works as follows: CPMs contain two Advanced Micro Devices 29050 microprocessors connected in a way that allows all processor inputs and outputs — address, data, instructions — to be immediately compared. If these comparisons yield different results, the processing is flawed. If they yield identical answers — the normal case — the processing result is valid. If an error is detected all processing results are halted, an error is logged, and recovery is attempted. Each machine cycle on the CPMs and IOMs is performed in lock-step by two separate processing channels, and comparison hardware ensures that each channel is performing identically. If a mis-compare occurs, the system will attempt retries where possible before invoking the fault handling and logging software in the operating system. The SAFEbus has four redundant data channels that are compared in real time to detect and isolate bus faults [A03].

Boeing required a continued, 10-day dispatch rate of up to 99.9 percent in the face of any failure, assuming a full-up system at the beginning of that period. With AIMS this was performed largely in software, by carrying extra copies of the applications, rather than many different processor modules. Honeywell's deterministic SAFEbus backplane technology allows another copy of a software application to be running and ready to go, so that, if needed, it could come on line without any interruption in system performance. A backup software function can transition into a primary function within two backplane clock cycles, a matter of nanoseconds. Outputs are not allowed to escape from the containment zone until such time that the processor environment can

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be verified. These approaches, combined with the redundant system architecture, help to explain Boeing's approximately 99.3 percent schedule reliability rate in 2002 for the B-777 [A03].

7.2.1   SAFEbus Backplane Bus

SAFEbus^{TM} was developed by Honeywell (the principal designers are Kevin Driscoll and Ken Hoyme [HDHR91, HD92, HD93]) to serve as the core of the Boeing 777 Airplane Information Management System (AIMS) [SD95], which supports several critical functions, such as cockpit displays and airplane data gateways. The bus has been standardized as ARINC 659 [ARI93], and variations on Honeywell's implementation are being used or considered for other avionics and space applications. The interfaces (called Bus Interface Units, or BIUs) are duplicated, and the interconnect bus is quad-redundant. Most of the functionality of SAFEbus is implemented in the BIUs, which perform clock synchronization and message scheduling and transmission functions. Each BIU acts as its partner's bus guardian by controlling its access to the interconnect. Each BIU of a pair drives a different pair of interconnect buses but is able to read all four; the interconnect buses themselves each comprise two data lines and one clock line. The bus lines and their drivers have the electrical characteristics of OR gates (i.e., if several different BIUs drive the same line at the same time, the resulting signal is the OR of the separate inputs). Some of the protocols exploit this property [R03].

7.3   Boeing 777 Flight Control System

The Boeing 777 is the first commercial transport built by Boeing to employ fly-by-wire primary flight control system. The advantages of the Fly-By-Wire system over the older mechanical system are:

- Reduction in airframe weight;
- Integration of several systems into a single system;
- Superior aircraft handling qualities; and
- Ease of maintenance.

A full discussion of the fly-by-wire system is contained in [SP00].

8. Advanced System Architectures in Regional Jet, Business Jet, Commuter, and Turboprop Flight Decks

While the most sophisticated systems and technologies generally manifest first in the large airline transports, there are two aviation systems that are incorporating centralized multi-processor, multi-process computing architectures similar to Integrated Modular Avionics of the B-777 and other advanced architectures. These integrated systems leading the way in general aviation are:

- Honeywell Primus Epic; and
- Rockwell Collins Flight Pro 21.

Manufacturers of general aviation avionics face additional challenges because they must be prepared to have their avionics used in many more different types of aircraft and must be prepared to support a large retrofit market.

8.1 Honeywell Primus Avionics Suite

The Honeywell Primus series is very popular and tends to be used on the larger high end business jets. There are three suites in the series, the 1000, the 2000, and the most recent addition, the Epic which incorporates that features of the 1000 and 2000, but implements a new centralized computing architecture [H98].

8.1.1 Primus 1000

The Primus 1000 was introduced in the 1990's and is installed on aircraft such as the Cessna Encore (see Figure 8.1), XLS, and Bravo. The Embraer regional jets ERJ 135 and 140 also use the Primus 1000 system. The Primus 1000 features 8x7-inch displays and Engine Instrument and Crew Advisory System (EICAS) to meet the operational requirements of both regional airlines and business aircraft; these are shown in Figure 8.2.

Honeywell designed the Primus 1000 to be cost effective by combining key functions into one integrated avionics computer, simplifying design, installation and maintenance, while increasing reliability. The Primus II radio management unit (RMU) operates as a back-up navigation display. The RMU also serves as a back-up display for the optional EICAS and functions as a controller for the optional Traffic Alert and Collision Avoidance System (TCAS). As a result, there are fewer units to purchase and maintain [H98].

8.1.1.1 Electronic Flight Instruments Systems

Honeywell's flexible Primus 1000 system uses 8x7-inch displays that can be optimized for the flight deck in a two-, three-, four-, or five-tube configuration. These displays integrate the functions of dozens of separate instruments to simplify cockpit scan and reduce pilot workload. The EFIS can be tailored to a particular aircraft's mission.

The Primary Flight Display (PFD), shown in Figure 8.3, combines Attitude Director Indicator (ADI) and Horizontal Situation Indicator (HSI) formats with airspeed, altitude, vertical speed and other information, such as resolution advisories for Honeywell's optional TCAS system. The

Multi-function Display (MFD), shown in Figure 8.4, offers a full spectrum of operational advantages, from weather radar and mapping displays, to a programmable checklist.

Figure 8.1. Photo of Cessna Encore, an aircraft utilizing the Primus 1000

The evolution from electromechanical instruments to EFIS systems has been a logical one. Certified for more than a decade, the cost of EFIS systems continues to decline while the cost of electromechanical systems increases. As a result, the EFIS allows operators to benefit from more capability, flexibility and redundancy, with increased reliability. As an added benefit for regional airlines, pilots flying EFIS-equipped aircraft have an easier transition to larger digital cockpits.

8.1.1.2 *Attitude and Heading Reference System*

Honeywell's Primus 1000 can be configured with a number of different attitude and heading systems; however, Honeywell recommends its new digital AHZ-800 AHRS, which uses an Interferometric Fiber Optic Gyro (IFOG) sensor to measure angular rates of motion. The IFOG measures the phase shift produced between two beams of light traveling in opposite directions through an optical fiber. Honeywell claims greater accuracy and reliability with less volume, weight and power use compared to current AHRS or gimballed gyros. The AHZ-800 has no moving parts to wear out and requires no special handling [H98].

A second option for low-cost attitude/heading sensing is a combination of Honeywell's analog VG-14A vertical gyro, C-14A directional gyro, RG-204 rate gyro and AG-222 accelerometers.

Figure 8.2. Primus 1000 installation on a Cessna Encore [Ce04]

8.1.1.3 *Integrated Display and Guidance Computer*

The IC-600 Integrated Avionics Computer (IAC), shown in Figure 8.5, is the primary avionics component of the Primus 1000. It combines the functions of an advanced fail-passive autopilot, flight director and display processor into one package. Integrating these functions also enhances the Built-In Test and fault isolation capabilities for improved maintenance [H98].

8.1.1.4 *Engine Instrument and Crew Advisory System*

The EICAS is an option with the Primus 1000 suite. As on the MD-11 and B-777, EICAS simplifies the flight deck by integrating the multitude of electro-mechanical instruments that previously were required to monitor engines and other aircraft systems. EICAS increases safety and decreases pilot workload by simplifying instrument scan and prioritizing the information and advisories presented. The EICAS incorporates logic to prioritize multiple events and provides several pathways for the collection and display of vital aircraft and engine data [H98].

8.1.1.5 *Inertial Reference System*

For applications that require inertial navigation capability, Honeywell offers the LASEREF® III. The LASEREF is a laser gyro-based system that is 60 percent smaller, 45 percent lighter and requires only 50 percent of the power of previous generation systems, while maintaining the same level of performance [H98].
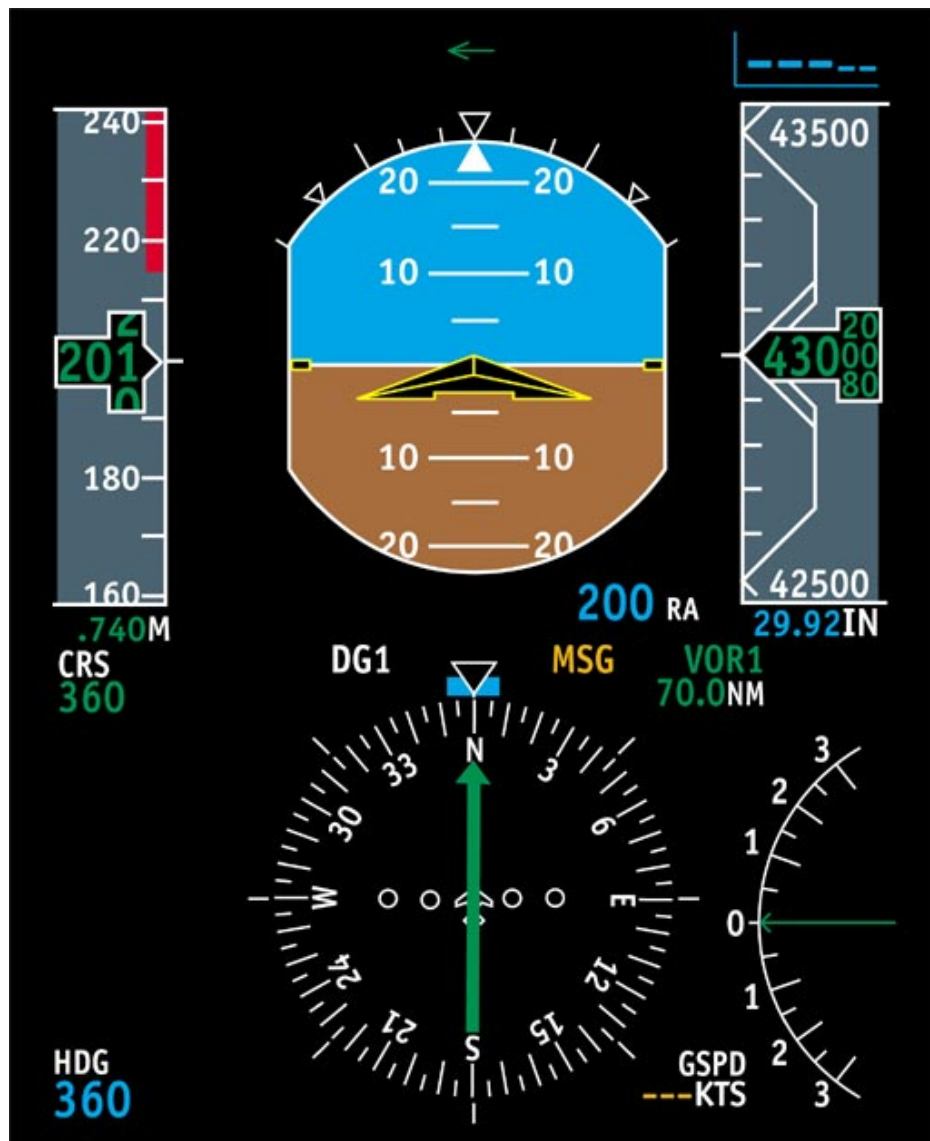
Figure 8.3. Primus Primary Flight Display [Ce04]

8.1.1.6   Flight Management System

For integration into the Primus 1000 suite, Honeywell offers the FMZ-2000. The FMZ-2000 offers full-mission performance customized specifically for each aircraft with SmartPerf^{TM}, or Smart (Learned) Performance. The FMZ-2000 features simplified flight plans, the storage of 255 company routes with up to 100 waypoints per flight plan, and full SID/STAR and approach procedures. As with most FMS systems, the FMZ-2000 performs lateral and vertical navigation, contains data for non-precision approaches, and automatic holding patterns. Airborne Flight Information Service (AFIS) data link capability is also provided [H98].

The FMZ-2000 is connected to a color control display unit. The system uses ARINC 429 system architecture in a two-MCU package that can be integrated into new aircraft [H98].
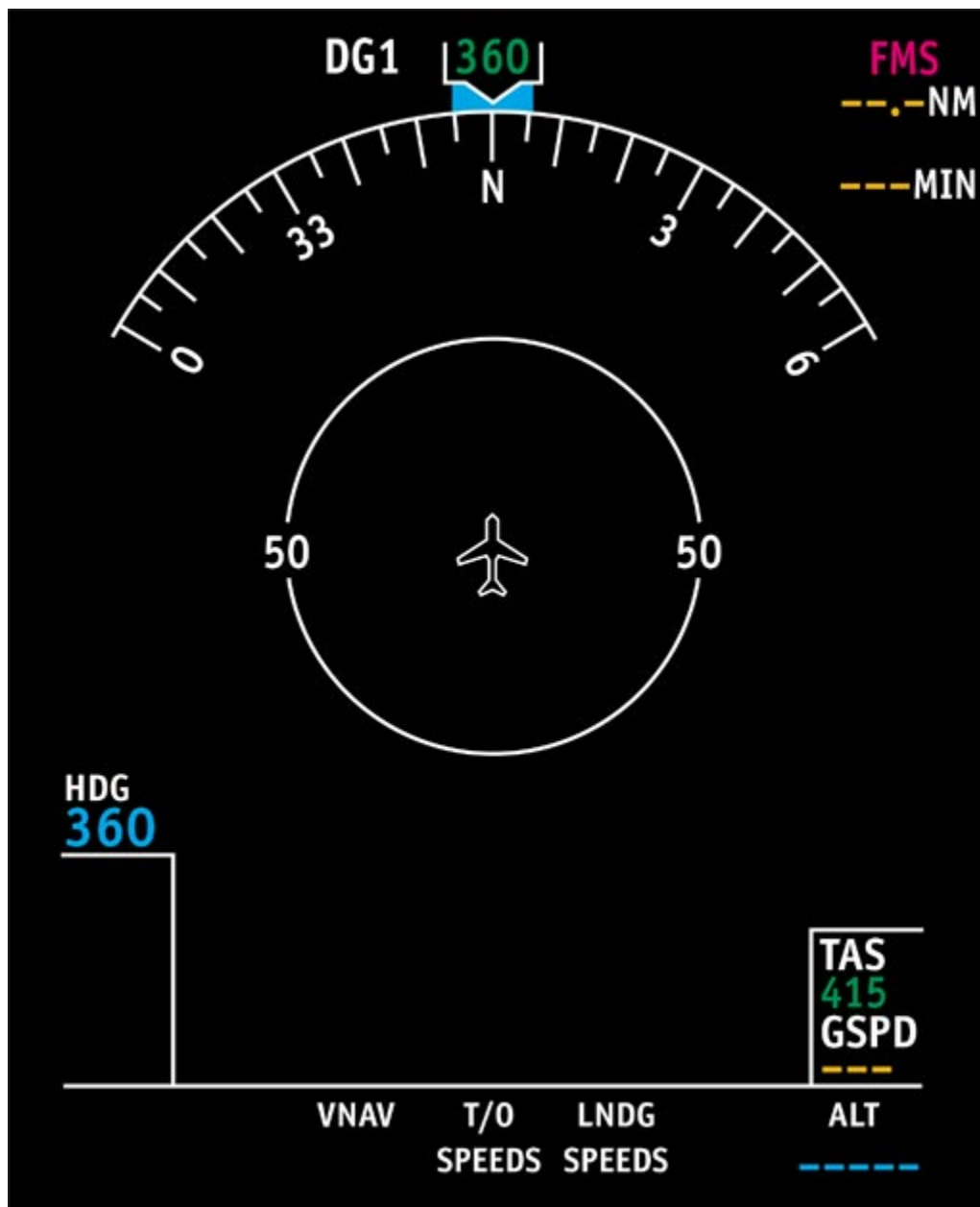
Figure 8.4. Primus Multi-Function Display [Ce04]

8.1.1.7 Integrated Radio System

Honeywell's Primus 1000 avionics system features the Primus II digital navigation /
communication / identification radio system in a dual configuration. A color flat-panel radio
management unit (RMU) and companion audio system centralize all frequency selection, display
and audio control.

Honeywell's RMU combines push-button and traditional tuning-knob operation to provide instant access and display of up to 12 stored communications frequencies and 12 navigation frequencies.

Figure 8.5. Integrated Display and Guidance Computer

The RMU is designed to provide an added level of safety by serving as a back-up navigation display. When EICAS is installed, the RMU also provides back-up engine instrument data.

The Primus II radio system utilizes four remote boxes that contain all communication and navigation functions. The communications units include VHF communications plus an optional transponder, including Mode A/C, Mode S or Mode S with diversity. Navigation units integrate VOR/ILS, extended frequency range ADF, with quality voice audio, and six channel scanning precision-compatible Distance Measuring Equipment (DME) [H98].

8.1.2   Primus 2000

Honeywell provides little information on the 2000 series. The PRIMUS® 2000 system, with a five-display-tube cockpit configuration, represents Honeywell's latest technology fully-integrated glass cockpit system. It is reserved for the largest high-end business jets such as the Cessna Citation X (see Figure 8.6 and Figure 8.7) and the Global Express.

Figure 8.6. Photo of Cessna Citation X, an aircraft utilizing the Primus 2000 [Ce04]

Figure 8.7. Photo of Primus 2000 installed on Citation X [Ce04]

Fully developed features of the proposed PRIMUS® 2000 system include:

- Large Display Tube EFIS System;
- Primary flight displays;
- Multifunction displays;
    - Navigation/map;
    - Weather radar;
    - TCAS;
    - Vertical profile;
    - Aircraft subsystem synoptics;
- Proven control concepts and panels;
- Certified symbology formats;
- Effective simple reversion capability;
- Interchangeable display units;
- Integrated Full Capability EICAS;
- Primary engine displays;
- Secondary engine displays;
- Fully integrated with EFIS, both operationally and architecturally;

- Crew advisory;
- Aircraft system synoptics;
- Checklists;
- Engine trend and limit monitoring and storage;
- Takeoff configuration warning;
- Integrated audio tone generation;
- Effective/certified bezel controls;
- Two dual-channel data acquisition units for aircraft interface;
- Dual Autopilot System; and
- Dual fail-operational CAT II flight director/autopilot.

Photos of the Primus 2000 MCDU and EICAS display and are shown respectively in Figure 8.8 and Figure 8.9. [H98]

Figure 8.8. Photo of Primus 2000 MCDU [Ce04]

8.1.3   Primus Epic

The Primus Epic is a considerable step forward for business/regional jet avionics because it is the first attempt to bring features of the centralized computing architecture seen in the B-777 into the cockpit of smaller aircraft. The basis of the Epic system is the Virtual Backplane Network^{TM}. This concept blends the cabinet-based modular capabilities of the Honeywell AIMS system for the Boeing 777 with the aircraft-wide network capabilities of the Primus 2000. The Epic architecture joins the Primus Epic's integrated modular units and line-replaceable units (LRUs) into a single aircraft-wide network. The system features a flexible framework and scalability - spanning the market from light turboprop regional aircraft and helicopters to heavy-class business jets [H98].

Figure 8.9. Photo of Primus 2000 EICAS [Ce04]

Displays consist of 8- x 10-inch flat-panel screens available in cockpit configurations that support movable navigation maps, ground-based weather, real-time video and aircraft utility systems control. As in the B777, pilots can choose traditional controllers or new on-screen cursor control devices developed to interface with the Windows-style operating system. Primus Epic also offers a voice command control system to control certain functions. The Primus Epic is being installed on new aircraft including the Cessna Sovereign, shown in Figure 8.10. A cockpit photo is shown in Figure 8.11 [H98].

8.1.3.1 Avionics Standard Communications Bus (ASCB)

Honeywell makes use of a new General Aviation-based avionics bus, the GAMA-standard Avionics Standard Communications Bus (ASCB). Honeywell's version of the bus provides high data throughput--equivalent to 100 high-speed ARINC 429 buses--using a tapped twinax wire. Similar to the current Honeywell ASCB network, the Primus Epic system consists of a dual-dual arrangement for system redundancy and provides a total network throughput capability of 20 megabits per second [H98], [H03].

Figure 8.10. Illustration of Cessna Sovereign, an aircraft using the Primus Epic Avionics Suite [Ce04]

8.1.3.2 Modular Avionics Unit

The Modular Avionics Unit (MAU) is a hardware cabinet containing field-replaceable modules that represent the "building blocks" of the Primus Epic system. The MAU incorporates input/output (I/O), processing, and data base storage modules linked to the Avionics Standard Communications Bus (ASCB) aircraft-wide network via a Network Interface Controller (NIC) module. The Virtual Backplane makes the MAU flexible and adaptive to customer requirements, allowing for more options in locating and mounting equipment on the aircraft.

The integration of computer processing into a single unit means that the MAU can be shared to perform multiple tasks previously requiring individual computer processors. This increase in integration results in improved power, weight, reliability, maintainability and volume. The

networking capability that allows data in any avionics function to be available for use by all functions eliminates point-to-point wiring and, in the case of a regional airline aircraft, saves about 400 lb [H03].

Figure 8.11. Illustration of Cessna Sovereign cockpit with the Primus Epic Avionics Suite [Ce04]

8.1.3.3   Digital Engine Operating System

Primus Epic software relies on an operating system called DEOS (digital engine operating system). "Engine" in this case has nothing to do with aircraft engines but is rather a computer architecture that separates the software applications from the hardware interfaces into different layers to streamline certification and software changes. The autopilot on the Bombardier Global Express is the first application of DEOS even though that aircraft is equipped with Primus 2000XP rather than Primus Epic.

DEOS does not attempt to handle as many different tasks in various windows as personal computer software in an office environment would. That's because an avionics system has to anticipate any failures and recover gracefully, without the kinds of computer crashes that office workers experience. DEOS took 10 years to develop, partly because of all of the partitioning required so that different software applications running independently on the same computer module do not interfere with one another. DEOS has a highly efficient environment, and at the same time provides a structure that enables different levels of functions (non-essential, essential, and critical) to operate on the same processor. This operating system permits engineers to develop software using standard tools, but still meet the FAA certification requirements [H03].

8.1.3.4 Integrated Sensor Suite

The Air Data Computer (ADC), Global Position System (GPS) sensor, and Inertial Reference System (IRS) or Attitude/Heading Reference System (AHRS) in use today have been replaced by the Integrated Sensor Suite (ISS), a complete primary sensor system. Each ISS function consists of three sensor components which include the small line-replaceable Inertial Measurement Unit (IMU), Air Data Module (ADM), and GPS Sensor Module. Raw information from the sensors is processed by the system to provide all the inertial, positional and air data information used by all other functions within the avionics system [H98].

8.1.3.5 Integrated Radio and Audio System

The Primus Epic digital remote-mounted radio system encompasses the standard navigation and communications functions, including VOR, ADF, DME, ILS, VHF Communication and Mode S Transponder modules. The radio system uses LRUs from the Honeywell Primus II integrated radio system, housed in dual remote mounted radio cabinets [H98]. The advantages to the operator are:

- Fewer units (less size, weight, & power use);
- Reduced wire count; and
- Extensive Built-In Test Equipment (BITE) and integrated maintenance features

8.1.3.6 Human Factors Design

Honeywell advertises the Primus system as being reengineered to enhance pilot performance and safety. The Primus Epic claims to bring large amounts of information into the cockpit for real-time use, resulting in increased safety through enhanced situational awareness and reduced pilot workload.

The Primus Epic has intuitive interfaces for the pilot to use such as cursor control devices (CCD), head-up displays and a Voice Command System. The Cursor Control Device (CCD), recently introduced by Honeywell on the Boeing 777, applies the point-and-click ease of the personal computer to the cockpit environment. Each pilot has a wall-mounted, arm-rest-style cursor-control device with a rolling ball that's moved by the thumb and a finger-operated trigger for selecting functions.

The CCD (see Figure 8.12) allows the pilot to control the many aspects of the display system similar to the mouse of the personal computer. The intent is that the pilot will intuitively know how to use the device because of the widespread use of personal computers. The use of CCD-controlled menus, Windows-based display pages and "soft keys" in lieu of hardware push-buttons reduces pilot workload while saving costs, weight and wiring associated with controllers.

The Primus Epic's Voice Command System (VCS) can also control certain functions. Using this technology, pilots can use a natural human communication method to command the system to access data, tune radios, call-up checklists, and perform other routine cockpit tasks [H98].

Primus Epic software architecture enables aircraft makers to customize cockpits to a greater degree than previously. And many of the manufacturers involved have chosen to do so in one way or another--such as using a track ball, thumb pad or joy stick as a pilot-input device in a

computer-style environment. Many of the modifications offered by the aircraft manufacturers improve situational awareness and customize the man-machine interface to enhance safety.

Figure 8.12. Honeywell Cursor Control device

8.2   Collins Pro Line 21

The Pro Line 21 is a new integrated avionics system developed at Rockwell Collins that incorporates the same centralized computing design philosophy found in the B-777 and other advanced architectures. Unlike transport architectures, however, a fundamental objective of the Collins Pro Line 21 is to achieve a system with the flexibility to be cost-effectively applied across a broad market range and to accommodate significant future functional change and growth. The system architecture supports applications in the corporate jet, regional airline, commercial air transport and military markets. These markets include the minimum-display-compliment, asymmetrical flight deck of the corporate entry level jet, to the multi-display flight decks of the corporate heavy jet, 30- to 100-passenger regional aircraft, large commercial air transport aircraft, and military transports and helicopters. The Pro Line suite can be used in both FMS and non-FMS equipped aircraft. The system architecture definition is driven by attributes including reduction of installed system cost, modularity of system elements to provide desired flexibility, maximizing the reusability of hardware and software system elements and system concepts and improvement of system availability [C04].

A wide variety of aircraft (see Figure 8.13) use the Pro Line 21 including the Cessna Citation CJ1, CJ2, and CJ3, the Raytheon Beech King Air 200 and 300, and the Bombardier Challenger 300.

Figure 8.13. Beech King 200 and the Cessna CJ1; Aircraft that use the Pro Line 21 avionics suite

The Collins Pro Line 21 Advanced Avionics System Architecture uses an increased amount of integration to provide a higher level of functional capability, fault tolerance and flexibility, as well as on-board diagnostic aids and other features designed to reduce crew work load and enhance the availability of system functions. Large format Liquid Crystal Displays (LCDs) and Cursor Control Dev ices (CCDs) integrate the display and control of system functions. Reducing the number of system displays and controls provides for a more intuitive flight deck. Functional processing is accomplished in an Integrated Processing Cabinet (IPC) using standardized modules and virtual machine / partitioned processing and field-loadable software. This provides a flexible, cost effective, reusable architecture with inherent ability to grow and true software mobility. The digital communication network achieves total connectivity among all subsystems. This connectivity is accomplished with data concentrators for legacy equipment and high-speed digital Local Area Network (LAN) Hubs for internal IPC data, IPC-to-IPC communication and interface to other high data rate users. This reduces system latencies, cross flight deck wiring and individual Input /Output (I/O) connections [C04].

8.2.1 Flight Deck Features

Collins Pro Line 21 avionics systems support many advanced features including terrain awareness, 3-D flight plan maps, electronic charting and real-time data link weather graphics. The system employs easy-to-use, graphical interfaces to provide pilots with enhanced situational awareness and intuitive display and control. A full line of communication, navigation and surveillance (CNS) equipment is available for the Pro Line 21 suite. The new sensors are significantly smaller and lighter than existing sensors, conserving space for future avionics technology insertions. They may be installed either as stand-alone units or as an integrated package. Operational upgrades are implemented through software changes. Collins Pro Line 21 CNS sensors support the transition from voice to data communications, enabling new capabilities in the flight deck, including automated digital messaging, automatic flight plan loading and the transmission of graphical weather information. A high-speed digital interface is used to convey both data and audio. The Pro Line 21 CNS sensors satisfy all current and planned surveillance requirements, including Mode S Elementary and Enhanced Surveillance to meet the upcoming requirement for operations in European airspace. The sensors are designed to accommodate upgrades to support future navigation enhancements and precision approach capability.

The use of large Active Matrix Liquid Crystal Displays (AMLCDs) (see Figure 8.14 and Figure 8.15) allows Pro Line 21 to convey more information and provide greater flexibility in format design. The benefit to the operator is a logical, uncluttered, informative display. AMLCD technology enables advanced features as 3-D flight plan map representations, real-life terrain depictions, on-board charting and real-time data link weather graphics [C04].

Figure 8.14. Active Matrix Liquid Crystal Displays (AMLCDs)

8.2.2 Pro Line Architecture

The core of the Collins Pro Line 21 Advanced Avionics System Architecture is the Integrated Processing Cabinet, IPC. Multiple IPCs perform application processing in the system as well as I/O data concentration from peripheral subsystems and devices. Throughout the system, wherever significant integration of function or concentration is used, increased redundancy of system elements is employed to mitigate the consequences of single point faults.

Figure 8.16 shows a simplified block diagram of one Pro Line 21 implementation that uses the Collins Advanced Avionics System Architecture. Typical Pro Line 21 system configurations have two or more IPCs. However, the architecture is scalable to a single IPC. For the typical system solution, multiple IPCs are used to achieve the computational channel redundancy necessary to support function availability requirements, system fault tolerance requirements, physical segregation requirements or meet physical installation constraints. The Pro Line 21 system operation is based on multiple, similar, asynchronous computation channels provided by the IPC s. Each IPC hosts one or more computation channels that provide the physical hardware platform and logical application software environment for hosting of system application functions.

The internal architecture of the IPC is shown in Figure 8.17. The physical hardware platform for an IPC computation channel consists of a dual LA N Switch, one or more Common Computing Modules (CCMs), dual Power Supplies and Environmental Control [C01].

Figure 8.15. Typical installation of Pro Line 21 Avionics as installed in the Hawker 800 XP

8.2.2.1 Communications

All functions must have the ability to access aircraft data that are provided in a timely manner. In addition, the communications function must be able to communicate with existing, legacy aircraft equipment. To provide availability and dispatch ability, a dual implementation of the local area network (LAN) is used. The LAN is used for inter-and intra-IPC communication and with other high data rate users as a replacement for the present ARINC 429 standard, which is limited in bandwidth and label availability. Also used is an open standards bus that supports the following LAN characteristics:

- Ability to support critical avionics data;
- Full-duplex operation;
- Very high composite bandwidth with concurrent path capability;
- Low latency with adequate determinism; and
- Bandwidth growth allowed as computing power continues to grow.

An Input /Output Concentrator (IOC) is used to provide the interface to legacy ARINC 429 - type equipment. The IOC concentrates, normalizes and schedules the 429 data, then uses a protocol conversion for receiving and transmitting data on the LAN. As with the LAN, each IPC

contains two completely independent IOC functions for increased availability and dispatch ability [C01].
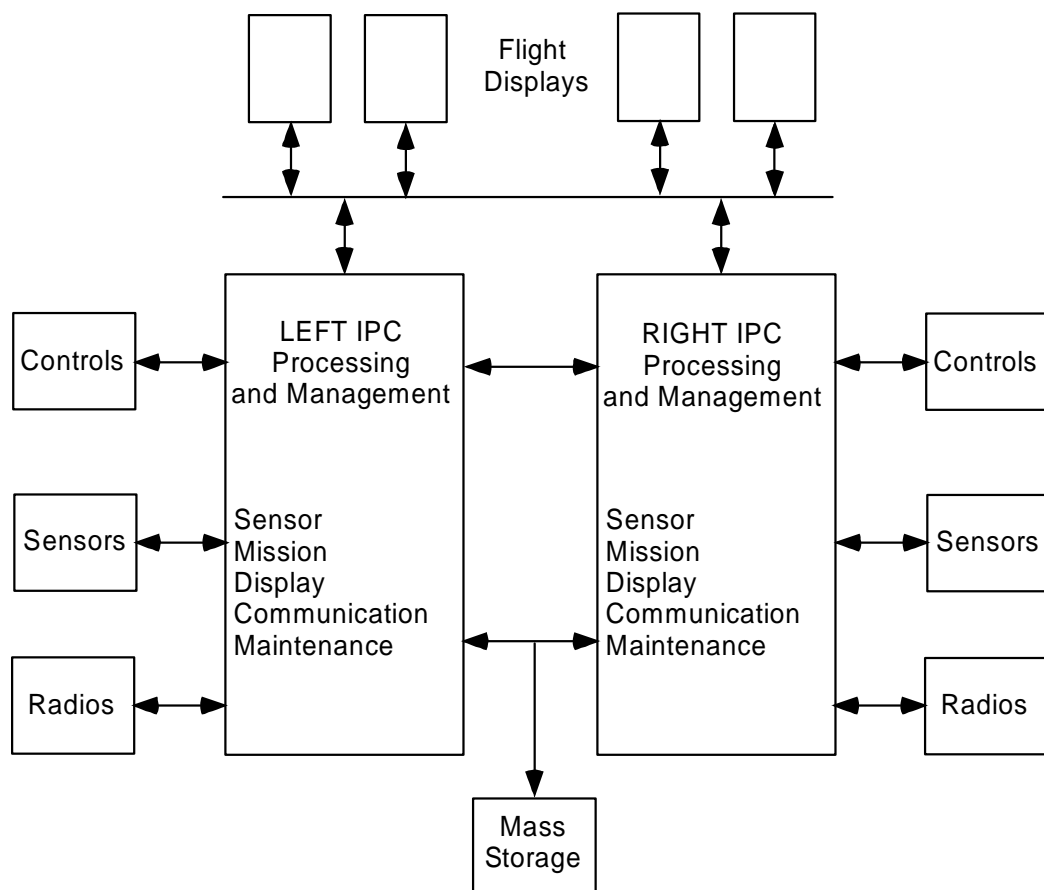
Figure 8.16. Typical architecture of Pro Line 21 Avionics suite using dual IPC configuration

8.2.2.2 Processing

One of the guiding principles used by Collins for processing hardware and software is to utilize open, standardized industry specifications where possible, with avionics- grade implementations. This approach minimizes design time and maximizes the availability of tools and experienced engineers. The Common Processing Resource (CPR) is a standard embedded processor design used in multiple applications. The prime interface to the CPR is an industry standard PCI bus. Optional CPR interfaces such as an additional PCI bus, an ISA bus and / or a SCSI bus, may be populated for very high bandwidth communication with display functions, medium-speed interfaces for data such as discretes or aural warnings, and a high-speed interface for peripheral devices such as a mass storage device. The CPR has a combination of hardware and layered system software that provides hardware independence from the processing platform. This hardware independence enables application software to be insulated from hardware changes in the underlying platform. Hardware independence is achieved by providing a Virtual Machine for the application software to execute on. Other applications of the CPR include combining the CPR with display graphics generation and control hardware to provide flight display functions and combining the CPR with non-digital bus interface hardware, analog-to-digital / digital-to-

analog converters, to provide a data acquisition function. Each CCM is a combination of hardware and software capable of hosting multiple applications at different criticality levels. Two CCMs in each IPC provide the processing throughput and functional redundancy required for the baseline system. Additional CCMs can be used for increased functionality. The CCM consists of a CPR that is coupled to a LAN bus node to support a redundant LAN connection to the system LAN switches. The CPR PCI bus provides high-speed interface to the LAN node from the processor [C01].
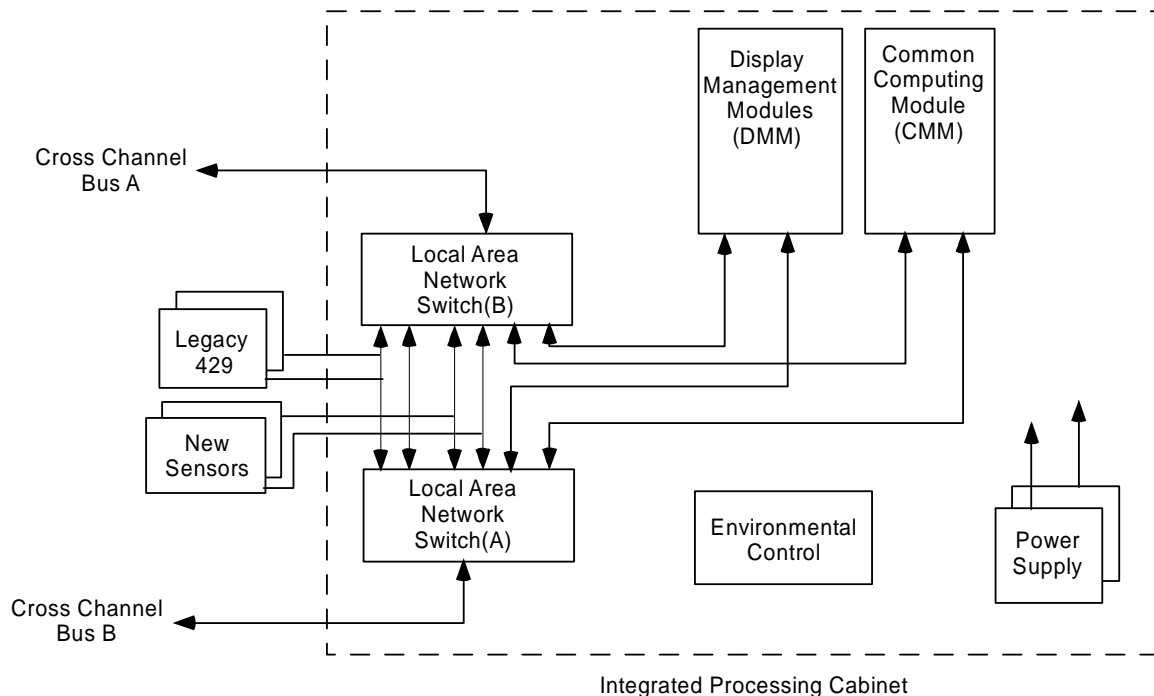
Figure 8.17. Internal architecture for an Integrated Processing Cabinet (IPC)

8.2.2.3   *Software Partitioning*

The Real Time Operating System (RTOS) is a layered system that provides a multi-processing, partitioned environment for application software. The partitioned environment eases system configuration and promotes cost savings through reuse and incremental certification. In addition to providing independence for the processing platform, the CPR also uses a message-passing method of communication that provides independence from the bus technology and network topology. This insulates application software from changes in the underlying network and network devices. In the Collins Pro Line 21 architecture, each application executes within its own partitioned environment that limits access to system resources. As far as the application software is concerned, each application is running in its own Virtual Machine and therefore its own partition. This is the basis of functionality and critical partitioning. Any attempt to violate another partition will trap to the kernel Operating System, and the appropriate recovery action will be taken. The memory, processor time and network resources required by each partition are defined at configuration time, using information provided by the supplier of a partition. Partitions are created at initialization time, and the partitioned memory use and network resources are validated and then allocated. At run-time, the RTOS enforces the partitioning of

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these resources. Each partition does not know that it is sharing the processor with other partitions. As specified in ARINC 653 (APEX), partitions are time-sliced by a fixed, preset schedule within a major, cyclic frame. Partitions do not have priorities. The RTOS also provides an interface for inter-partition communication. A partition does not know the location of the source or the destination partition for any inter-partition communication message that it sends or receives.

Again, to increase availability and dispatch ability, dual power supplies and distribution systems are used in the IPC. Power line transient protection is provided along with a load shed capability to minimize power requirements during emergency battery operation. The power supplies are designed to be fail-independent so that failures occurring within either power supply do not affect the other power supply. Each power supply in the architecture normally supports only a portion of the load in the IPC. This allows the internal components of the power supply to be operated at greatly reduced levels during normal operation, thus improving power supply reliability. However, each power supply has the capability to support the IPC's full load requirements. This improves the fault tolerance of the system [C01].

9. Light General Aviation Flight Decks

Light general aviation has seen a revolution in avionics capability since the mid 1990s and the advent of GPS. Avionics platforms have moved from electromechanical instruments and analog navigation radios to amazingly sophisticated avionics in just a few years. Garmin and Eclipse's Avio have led the development of very sophisticated nav-com units that combine GPS, VOR/DME, voice communications, lateral guidance, and moving map displays all in one unit. Recently, even these devices have been eclipsed by the stunning release of the Garmin 1000, a fully integrated flight deck for light general aviation. Additionally, Eclipse Aviation has chosen to develop a fully integrated suite of avionics for their new microjet, the Eclipse 500. Most recently, Bendix King has announced its intent to join the market with its own integrated system, called the APEX (Not to be confused with the software architecture APEX).

9.1 Garmin G1000

The G1000™ is a completely integrated avionics system designed to fit a broad range of aircraft models. It has been installed in light piston aircraft that have classically been all mechanical/analog devices such as the Cessna 182 (see Figure 9.1 and Figure 9.2). At the other end of the envelope, the G1000 is standard equipment on the new Cessna Mustang, a small six-place jet aircraft as shown in Figure 9.3.

Figure 9.1. A conventional light piston cockpit

Figure 9.2. C-182 cockpit equipped with the G1000

Figure 9.3. Cessna Mustang cockpit with the G1000

The G1000 is an all-glass flight deck that presents flight instrumentation, location, navigation, communication, and identification data on large-format, high-resolution displays. The digital data presentation on the G1000 puts all flight-critical information literally at the pilot's fingertips. The main features of the G1000 are summarized as follows [G04]:

- PFD/MFD Control Display Units (CDUs) - Consisting of two10.4 inch XGA displays offering the highest resolution (1024 X768) in their class;
- Dual NAV/COM Integrated 16 watt transceivers with selectable 8.33 kHz channel spacing;
- Dual GPS - IFR En route/Approach Certified and WAAS upgradeable units built on proven GNS 430/530 technology;
- Fully Integrated Mode S Transponder with Traffic Information System (TIS);
- Digital Audio Panel with 3 x COM, 2 x NAV, Pilot/Crew Isolation intercom capability with 6-place audio, DME, ADF, HF, Sat-phone, entertainment, and audio playback capability (2.5 minutes);
- Attitude & Heading Reference System (AHRS) - Solid state system capable of in flight and on the move initialization;
- Solid state three-axis magnetometer providing full three-axis vs. two-axis magnetic field information in all flight attitudes;
- PFD/MFD reversionary mode (In the unlikely event of display failure, PFD and engine data can be swapped between displays providing seamless transition and increased safety);
- CDUs equipped with an infrared port to accommodate data entry (flight plans, etc.) and engine trend monitoring via a handheld Garmin PDA in development;
- Stormscope - WX500 displayed on both the PFD and MFD with "Strike Ageing" history;
- Weather - Flight Information System (FIS) utilizing the next generation GDL 69A satellite weather data link with XM Radio entertainment. XM radio and Weather Worx (WxWorx) subscription optional;
- EICAS - Engine/Airframe Indication and Crew Alerting System features a trend monitoring interface through Infrared (IR) port using handheld Personal Digital Assistant (PDA) in development;
- Solid State Digital Air Data Computer (ADC) to compute and display TAS, CAS, VSI, TAT, wind direction and velocity;
- Topographic relative terrain and obstruction clearance mapping to enhance situational awareness and safety;
- Re-designed electrical system for enhanced safety with a standby battery to power the PFD, AHRS, ADC, magnetometer and one NAV/COM/GPS for up to one hour;
- "Jet-like" lighted switch and circuit breaker panels; increased safety and redundancy through a dual battery design and traditional standby airspeed and altimeter instrumentation and non-electric engine driven vacuum attitude gyro;

- Simplified Line Replaceable Unit (LRU) system architecture which includes identical and interchangeable CDUs and various remote mounted equipment to minimize down time and cost of operation;

- Proven Ethernet architecture for safe and reliable operation with room for future expansion;

- Optional - Terrain Awareness and Warning System (TAWS B) providing enhanced situational awareness with aural warning. Software upgrade (Optional future upgrade);

- Optional - 3D Terrain further enhancing situational awareness. This feature will most likely be bundled with TAWS B requirements (Optional future upgrade);

- Optional Traffic Advisory System (TAS) TCAS with integration of KTA 870 TAS (Optional future upgrade); and

- Optional Automatic Direction Finder (ADF). (Optional future upgrade).

Garmin's G1000 uses an attitude heading and reference system (AHRS), which uses algorithms to calculate all three axes of flight data. While competing glass panels rely on AHRS technologies, as well, the G1000 has been the only system that can initialize itself on the move. That means, should there ever be an interruption of power, the G1000 can reinitialize in flight, while other systems require the pilot to land. The G1000 currently does not contain any auto flight capability, so an external autopilot still must be used. On the C-182, a Honeywell KAP-140 Dual Axis autopilot with altitude pre-select and GPS roll steering are used. GPS roll steering is the terminology used for lateral guidance in the light aircraft domain [L04]. The G1000 is able to provide lateral guidance commands directly to the autopilot. These aircraft have no auto-throttle, so vertical guidance always has to be managed manually (using the autopilot) [L04].

9.2 Eclipse 500 Avio Avionics Suite

Known as Avio, the Eclipse 500 avionics system is a joint venture between Avidyne, BAE Systems, and General Dynamics. Avio is designed to replace nearly 30 individual boxes with four identical chassis units. Its major components are the electric power distribution system and the aircraft integrated electronics unit (AIEU) with dual FADEC channels, dual 3-axis autopilot and auto-throttles [D03].

Avio's Total Aircraft Integration provides centralized control of all aircraft systems – everything from engine controls to fuel system management to cabin temperature and pressurization control. Avio presents this information in its sophisticated cockpit suite, extending the reduced workload benefits of modern "all-glass cockpits" to management of the entire aircraft. This level of Total Aircraft Integration and the resulting safety enhancements have previously been available only in advanced military aircraft and commercial jetliners. Eclipse uses the power of digital electronics to make this capability standard in the Eclipse twin-jet. Important features include:

- Comprehensive avionics functionality;

- Electronically controlled aircraft;

- Advanced electronic power distribution system;

- Full integration of major systems; and

- Solid-state circuit breakers, switches, and contactors.

9.2.1   Avionics and Instrumentation

The Eclipse 500 comes equipped with comprehensive standard avionics as seen in the cockpit illustration in Figure 9.4 . The pilot interface is a streamlined glass cockpit that features two primary flight displays (PFDs) and one multi-function display (MFD) which are controlled by selection keys and knobs on the displays or by a keyboard at the pilot position.

Figure 9.4. Eclipse 500 cockpit with Avio avionics suite

The PFDs and MFD provide the pilot with high-resolution display of all flight parameters, engine and system performance data, and total system control. Dual digital communications and navigation radios are part of the PFDs and are tuned using knobs on the PFD panel. The communications radios have the ability to monitor more than one frequency and allow the pilot and copilot to transmit on separate frequencies.

Systems control is accomplished via the MFD. These systems include fuel, electrical, engines, environmental control, de-ice, lighting and pressurization.

To ensure availability of critical instruments, backup instruments are embedded in the MFD. In addition, both PFDs and the MFD have a reversionary mode that allows it to transfer its information to one of the other displays if required.

Avio's avionics and pilot information and control (APIC) feature provides all system data through dual primary flight displays and center panel multifunction display (MFD). The system also captures health-monitoring data and troubleshoots problems [E04].

9.2.1.1   Standard Avionics Features

Avionics functionality for communications, navigation, situational awareness and flight guidance and control are all integrated into Avio.

VHF communication is provided with dual, digital 760-channel, 16-watt radios including 8.33-kHz capability. The communication radios have the ability to monitor more than one frequency and allow the pilot and copilot to transmit on separate frequencies.

The digital VHF radios are located in the PFDs.

Dual GPS navigation, certified for IFR en route and approach capability, and dual VOR/ILS navigation systems are integrated in Avio. An integrated flight management system (FMS) with performance computing capability is also included.

Navigational capability includes an active moving map display, flight path predictor, advisory vertical navigation (VNAV), approach and departure procedures, nearest airport displayed on map, and automatically nominated VOR/ILS frequencies.

Dual Mode S Transponders are also integrated in Avio.

Color weather radar, terrain awareness database, Traffic Information Services (TIS), and data-linked graphical weather are integrated in Avio. Support capability for Automated Dependent Surveillance – Broadcast (ADS-B), Wide Area Augmentation System (WAAS) and Terrain Awareness and Warning System - Broadcast (TAWS-B) is also included.

In addition, the Eclipse 500 will be Reduced Vertical Separation Minimum (RVSM) group certified [E04].

9.2.1.2   Auto-flight Features

A 3-axis autopilot, dual AHRS with air data computer, and an auto-throttle are integrated in Avio. The presence of the auto-throttle is quite unique on an aircraft of this size. This feature enables full automated flight and takes advantage of the vertical trajectory optimization in the FMS [E04].

9.3   Honeywell/Bendix King APEX

Honeywell advertises the APEX as '*the most technologically-advanced cockpit in general aviation comes with a powerful pedigree*'. Honeywell presumably has leveraged off its airline transport technology to create APEX. The APEX is aimed specifically at the retrofit market; however, it is available on several new aircraft, including the GROB Ranger G 160 [B04].

9.3.1   Displays

The APEX/R system architecture uses one or two primary flight displays (PFDs) and a single multifunction display (MFD), as seen in Figure 9.5. The crystal-clear Active Matrix Liquid Crystal Displays (AMLCDs) feature state-of-the-art resolution, and provide wide viewing capability to allow cross-cockpit scanning by either pilot. With a nearly unlimited dimming potential, and a super bright backlight, pilots are guaranteed optimal display readability at any time of day, in any weather conditions [B04].

9.3.2   Visual Cueing and Control

 Honeywell has developed a new integrated presentation technique called Visual Cueing and Control (VC2) that attempts to replicate cues natural to VFR flight in any flight conditions. The "Enhanced T" replicates the "Basic T". Conformal symbology increases a pilot's situational awareness and ability to navigate the aircraft by presenting a view that conforms to the outside world. Spatial flow integrates texture, perspective and color cues to give the pilot better depth and attitude perception – leading to faster reaction time [B04].

Figure 9.5. Bendix King APEX suite

9.3.3 Flight Management System

The Flight Management System (FMS) gives pilots exceptional automatic navigation, guidance, and trip planning capabilities. It also reduces workload by automating many routine tasks and manual computations, and providing crucial information to help manage the flight path, from origin to destination. The system has a provision for autopilot/flight director coupling, both laterally and vertically (for WAAS approaches). The FMS computes the current airplane position, velocity and wind with unparalleled accuracy, using information from the onboard sensors [B04].

9.3.4 ADAHRS

Honeywell's KSG 7200 Air Data, Attitude and Heading Reference System (ADAHRS) is used in the APEX suite. The ADAHRS is a dual-channel RVSM-compliant unit that provides altitude, airspeed, air temperature, heading and the aircraft's orientation relative to the horizon. Each channel features Honeywell Micro-Electro-Mechanical Sensors (MEMS) for attitude and rate as well as Honeywell-produced solid-state pressure transducers for air data [B04].

9.3.5 Flight Control System

The completely digital APEX/R Automatic Flight Control System (AFCS) is derived from Honeywell autopilot technology. The autopilot is based on a single-channel dual processor architecture, it is fully fail-passive to maximize in flight control safety. The AFCS and FMS are integrated together on the APEX [B04].

9.3.6 TTP Databus

The Honeywell AXDB bi-directional databus (using Time Triggered Protocol – TTP™) eliminates over half the wires required in light jet and turboprop aircraft. This leads to lower costs for installations and upgrades, and reduces the weight, increasing the load-carrying capability of the aircraft. It improves information sharing by allowing functions to be distributed, as required, to maximize the use of I/O and CPU resources. The databus communicates with all other components in real time [B04].

9.3.7 Data Fusion

The APEX/R integrated cockpit fuses together safety information from the four major airborne safety systems – positioning, weather avoidance, traffic advisories and terrain awareness. All data are gathered, coordinated and prioritized through sensors such as data link weather (FIS), traffic (from TIS to TCAS), and Enhanced Ground Proximity Warning Systems (EGPWS) [B04].

9.3.8 CNS Capability

The APEX/R integrated digital radio system embodies the latest evolution in Honeywell radio technology. APEX is equipped with a VHF Data Link (VDL) Mode 2 receiver that enables high-speed data link weather, with planned upgrades to VDL Mode 3 to meet the FAA's announced plan for NEXCOM. APEX implements a Radio Tuning Control function integrated in the PFD Control Panel that utilizes the display capability of both the PFD and MFD. This offers flexibility for different radio configurations, clear access to controls, redundancy and reliability [B04].

10. Additional Manufacturers and the Retrofit Market

There are additional manufacturers of avionics that do not build integrated systems but do build high quality single components that can be installed at customer request in new aircraft or that support the aircraft retrofit market. Two such companies are Universal Avionics [U04] and Chelton Flight Systems [Ch04].

10.1 Universal Avionics

In 1981, Mr. Hubert Naimer founded Universal Avionics with a vision of developing a flight management system (FMS) for corporate aviation. The first UNS-1 FMS was unveiled to the industry at the National Business Aircraft Association Convention in 1982. Currently Universal manufactures FMSs, Navigation sensors, TAWS systems, flat-panel displays, satellite communication systems, and cockpit voice recorders [U04].

10.1.1 Universal FMS

Since introducing the original UNS-1 Flight Management in 1982, Universal has continually taken the industry forward with a pilot-focused vision of flight management. Today's Super Flight Management Systems (see Figure 10.1) build upon popular UNS market-proven product design, offering new features and interfaces, and providing growth capabilities for the new era of Communication, Navigation, Surveillance/Air Traffic Management (CNS/ATM) evolving in the world flight environment [U04].

The product line has evolved into a complete family of Flight Management Systems positioned to target overlapping segments of the market from turboprops, light jets and helicopters, through medium and large business class aircraft, to regional and major commercial airliners.

System features provide pilots with the ability to seamlessly fly all procedures from takeoff to touchdown along with optimized fuel and performance parameters. System features include:

- High resolution, sunlight readable, color flat-panel display;
- Internal 12-channel GPS/GLONASS receiver;
- Pilot and Company route storage;
- Nav Database includes SID/STAR procedures, airways, holding patterns, approaches, plain-language navaid references;
- Procedural leg guidance per ARINC 424;
- Heading Mode and PVOR Tracking;
- VNAV with computed Top-of-Descent, Target Vertical Speed and Vertical Direct-To;
- Holding patterns with auto entry;
- 3-D Approach Mode for "ILS-like" guidance on all non-precision approaches;
- Fuel Management;
- Performance Management for specific aircraft;
- Frequency Management option;

- UniLink compatible;
- TAWS compatible; and
- LAAS and WAAS upgradeable.

Figure 10.1. Universal Avionics FMSs

10.1.2 TAWS

The Universal Terrain Awareness and Warning System (TAWS) is designed to provide the pilot with increased situational awareness and reduce the possibility of accidents associated with Controlled Flight Into Terrain (CFIT). The TAWS system takes aircraft state information from onboard sensors along with flight path intent information from the Flight Management System and combines these with its own internal worldwide terrain database.

TAWS provides the pilot with hazard advisories along with real-time graphical displays of the terrain surrounding the aircraft dynamically displayed in three views: Map View as if looking down from above, Profile View as if looking from the side, and a unique 3-D Perspective View. These views are available on video-capable devices such as the MFD-640 Flat-Panel Multi-Function Display and FMS Control Display Units with 5-inch screens — both available for new and older aircraft alike. A Map View of terrain is available via ARINC 708/708A for radar displays [U04].
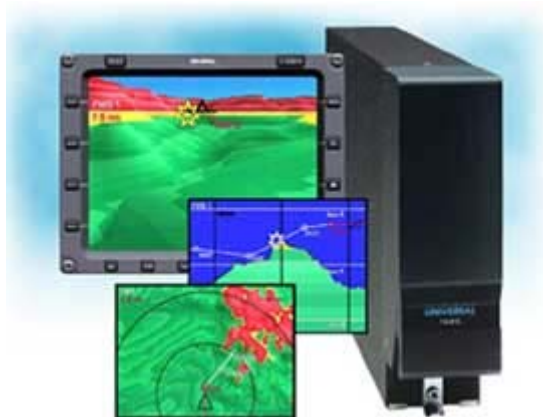
Figure 10.2. Universal Avionics TAWS systems

10.2 Chelton Flight Systems

Chelton Flight Systems is part of the Chelton Group, a US subsidiary of Cobham PLC. The main products Chelton offers for general aviation are 3D synthetic vision, terrain awareness, and highway-in-the-sky [Ch04].

10.2.1 3D Synthetic Vision

The Synthetic Vision technology system delivers a realistic, real-time 3D depiction of terrain and large man-made structures. The display provides 'smooth' analog flow, to closely emulate the 'out-the-window' display. The synthetic vision system is shown in Figure 10.3.
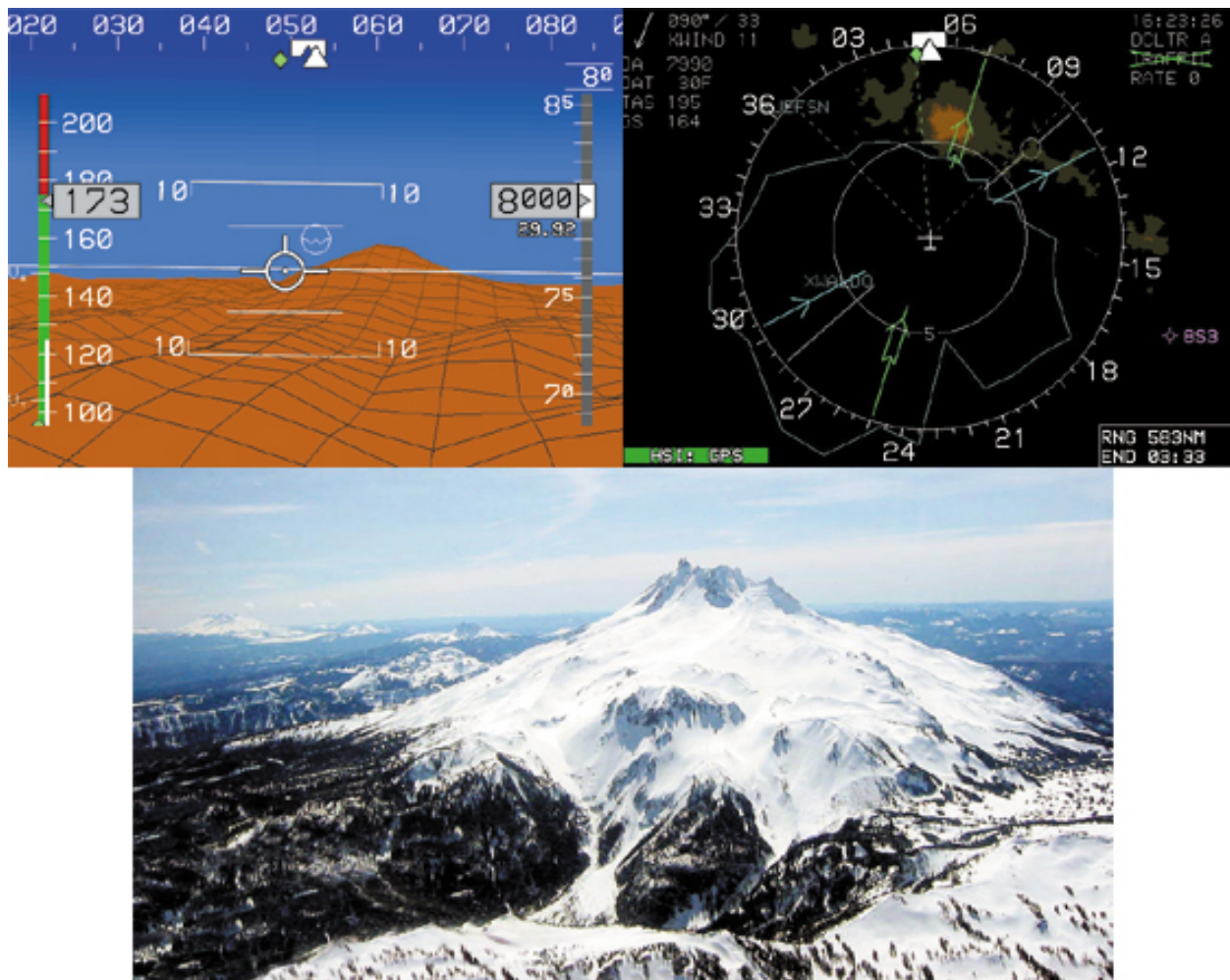
Figure 10.3. Chelton Flight Systems synthetic vision

10.2.2 Terrain Avoidance

In an effort to minimize Controlled Flight Into Terrain (CFIT) accidents, the FAA has mandated installation of TAWS on all turbine-powered aircraft configured with six or more passenger seats in the U.S. The Flight Logic EFIS provides TAWS functionality that meets the requirements of

the FAA mandate. The system includes Class C TAWS. Class B and Class A TAWS are available as options. Additionally, Chelton's EFIS is the only system in the world that provides 3-D terrain visualization directly on the Primary Flight Display. The TAWS product is shown in Figure 10.4 [Ch04].

Figure 10.4. Chelton Flight Systems TAWS system

10.2.3 Highway in the Sky

The Highway-In-The-Sky (HITS) technology system makes creating and flying a flight plan much easier than traditional displays. Instrument approaches become so much easier. The display for the HITS system is shown in Figure 10.5.

Tapping topographical databases, the HITS technology plots a 3D "tunnel" along the desired route of flight. The skyway appears as a series of green boxes superimposed over the 3D Synthetic Vision in the Primary Flight Display (PFD). The pilot or autopilot guides the aircraft through the boxes on the PFD to follow the flight plan through all waypoints.

On approach, the green HITS glide slope boxes guide the approach and descent. As the threshold is approached, the depiction of the runway grows larger and corresponds to the view out the window [Ch04].

Figure 10.5. Chelton HITS Display
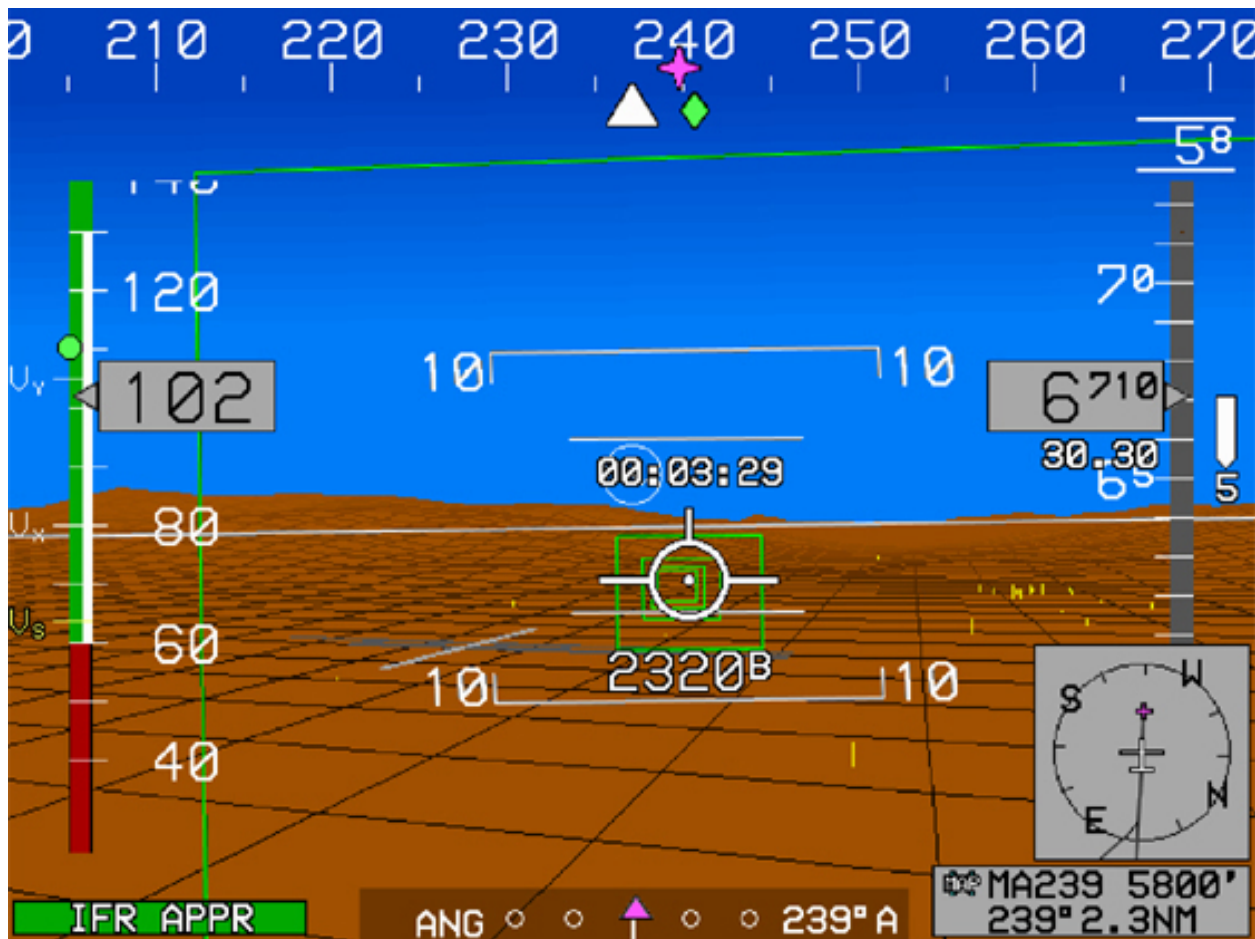
10.3 Retrofit Market

There is a large segment of the avionics industry dedicated to the installation of new digital avionics into older aircraft that were built prior to the advent of digital avionics. Elliott Aviation is a prime example of such an organization. Elliott Aviation has become a leader in business aviation, where it develops formal modifications to existing aircraft to install new equipment. The formal modification of any aircraft requires the issuance of a Supplemental Type Certificate (STC) from the FAA which is basically an addition or addendum to the original type certificate.

An example of such a retrofit is seen in the installation of a new Universal Avionics package in an older Lear 35 as seen Figure 10.6. The Lear 35A STC adds new capabilities and reduces pilot workload, as well as improving safety by dramatically increasing situational awareness. This STC includes four Universal EFI-550 Flat-Panel Integrated Displays with a Universal MFD-640 and Universal TAWS (Terrain Awareness and Warning System). The Universal TAWS is integrated to display on the MFD-640 in a VGA graphical format and exceeds all requirements for the FAA Class A TAWS mandate. The FPID upgrade program replaces aging, expensive to maintain electromechanical flight instruments while enhancing the reliability and operational safety of the aircraft. Similar STCs are available for the Beech King Air series aircraft, the Hawker 700, and the Falcon 10 [El04].

Figure 10.6. Elliot Aviation retrofit of a Lear 35 with Universal Avionics

11. Advanced System Architectures

The common theme of this document is to illustrate the current trend in digital avionics development which is to move away from distributed architectures towards centralized multi-processor, multi-process, avionics. This trend in avionics has been demonstrated with first generation systems such as the AIMS cabinet on the Boeing B-777, followed by systems such as the Primus Epic and the Flight Pro 21. However, there are number of reasons to suggest that this trend may not result in optimal architectures in the face of rapidly changing computing technologies. In this section we revisit the virtues of distributed systems and show how a new generation of distributed architectures may hold promise [SP00].

11.1 Technology Trends

The large commercial markets for computing technologies have continued to reduce the cost of computing resources and have provided smaller cheaper and more reliable hardware with considerably higher performance. For instance, an FMC of the early 90's that required a large 10" wide box can now be implemented on a single card [SP00]. Similar advances have occurred with sensors displays and data buses.

At the same time, the complexity of the systems on board aircraft has increased. Aircraft carry technologies such as full digital auto-flight systems, fly-by-wire flight controls, FMS, and highly automated systems management software. Most of the development of these products is in software rather than hardware. Today, software consumes 70-80% of the development budget for new avionics and is by far the highest cost and schedule risk.

Therefore it becomes hard to justify developing large centralized computing structures to minimize the cost of hardware development, considering that additional software in the form of specialized operating system and partitioning software must be developed to accommodate the centralized architecture. In short, the centralized architecture tends to minimize the cost (size, weight, power usage in addition to acquisition cost) of hardware at the expense of more software when the natural market trend is already to minimize the cost of hardware.

Because the centralized architectures may require software to be hosted on different platforms, much effort has to be made to insure that the application software is independent of the hardware, adding additional cost to software development and testing. Additionally, the re-hosting of existing software on new hardware with new operating systems bears an additional cost in terms of software development/ reuse [SP00].

11.2 Advances in Distributed Architectures

Two advances have given renewed interest to distributed architectures. These are (1) the advent of "Smart" peripherals, and (2) high speed serial buses.

11.2.1 Smart Peripherals

The reduction in the size of electronics has enabled boxes that used to be stored in a centralized location to be moved to various locations in the aircraft. Examples of these devices along with their location include:

- Full Authority Digital Engine Control (FADEC) - On the engine;
- Air Data Module (ADM) - Fuselage skin;
- Cabin entertainments systems - Cabin; and
- Auto-throttle actuators - under floor.

It is possible to provide considerable functionality within the peripheral devices without increasing their size using modern micro-circuits. It is likely that the trend will continue and smart peripherals will occupy displays, flight control actuators, landing gear sensors, fuel quantity indicators, and radios and navigation sensors. Driving this trend is the potential reduction in wires and connectors, robustness to noise interference, and reduced uncertainties as to fault location [SP00].

11.2.2 High Speed Serial Data Buses

Serial digital data buses have been use on both civil and military aircraft for many years. ARINC 429, which is a single-transmitter multiple-receiver format operating at either 12 Kbps or 100 Kbps, is used on all modern civil transport aircraft. The disadvantage of this bus is that it can only carry data from one source and so each item needs as many inputs as the number of buses that it expects to receive data from.

The Boeing 777 is the first aircraft to move away from ARINC429 and use ARINC629 in which all connected units can transmit and receive via a single port connection. This bus operates at 2 Mbps. While the bus is reliable and reasonably robust, it is still slow when compared to a standard PC Ethernet connection of 100 Mbps. More recently, fast networking buses are starting to appear that are based on commercial (non-aviation) standards. The industry has started work on Ethernet and the first example of FDX (Full Duplex Ethernet). Airbus is planning to a variant of FDX (AFDX) as the main avionics and system buses on the A380. Likewise, Boeing is considering the use of AFDX on the B7E7. At this point, it is unlikely that ARINC629 will be used on any aircraft other than the B777 [SP00].

11.3 Smiths Industries Common Core System for the B7E7

The Smiths Industries Common Core System (CCS) is an integrated, open architecture, high integrity, networked system providing aircraft systems with computational and input/output resources. CCS provides the following high level services to Hosted Functions:

- Common Computing Environment Service;
- Data Distribution Service; and
- I/O Interface Service.

The CCS, while still a centralized architecture, takes advantage of high speed data bus and smart peripherals where possible [Sm04].

11.3.1 Common Computing Resource Cabinet

The CCR enclosure contains Multiple General Processing Modules (GPM), Dual Redundant Power Conditioning, and cooling systems (see Figure 11.1). The software architecture is based on the ARINC 653-1 partitioned operating environment (as detailed in Section 4) and hosts aircraft system applications in robustly partitioned computing environment. The CCR system is a high integrity design with less than 10_{-9} undetected failures per flight hour.
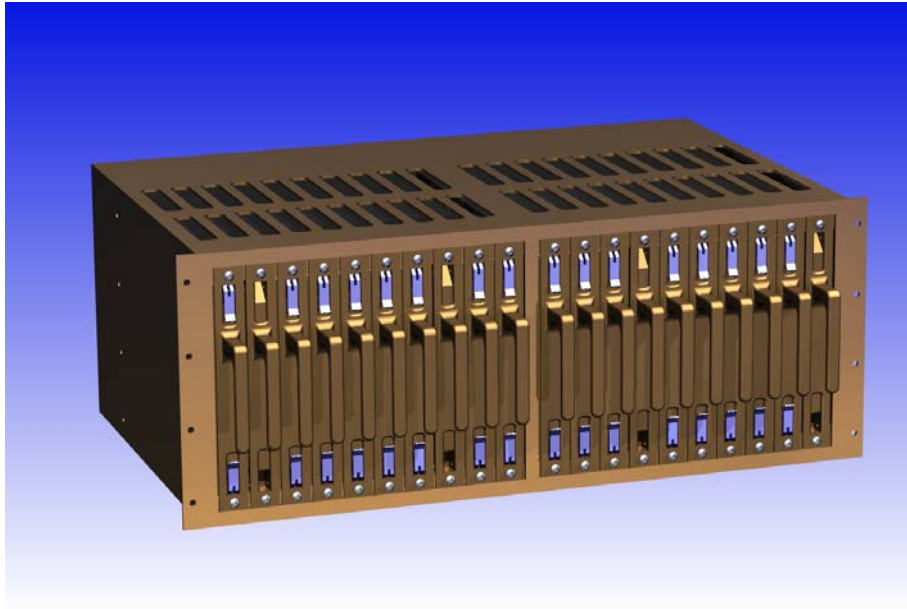
Figure 11.1. Illustration of the CCR Cabinet

Each GPM hosts a Real Time Operating System that provides an ARINC 653- Sup 1 and DO-178B level A-compliant partitioned operating environment. The partitioned operating environment that is provided as part of the Operating System in the GPMs is the Software Common Operating Environment (SCOE). Smiths' offering is based on a Wind River RTOS and is being jointly developed by Wind River and Smiths. The ADA runtime is being provided by ADA Core Technologies. This industry standard application interface is being developed and certified as part of the referenced programs. Further, the SCOE is being extended to operate on the newer MPC74x7 family of processors as part of the C-130 AMP development program making it fully compatible with the production design of the 7E7 GPM.

The SCOE supports both ADA and C software languages, the primary languages used for avionics applications. A three-tiered health management capability allows several fault recovery levels to be implemented. The SCOE also provides ARINC 615A data load capability for on-board loading of applications, data bases and configuration files.

The SCOE comes complete with a full COTS tool development suite and is hosted on COTS hardware to provide a very economical software development capability.

The core unit of the CCR is the General Processing Module (GPM) which is application ready with the ARINC 653 operating environment, and a fail passive, high integrity design as shown in Figure 11.2. Each GPM includes an ARINC 653 partitioned operating environment and machine specific software infrastructure such as interface drivers, Bit and data load. At the core of the GPM is MPC 7447 PowerPC. Self checking triplex processor outputs are voted on every memory write operation, mis-compares are flagged, and disagreeing data are blocked. This provides undetected failure rates on the order of 10^{-10}/flt hr, supporting the most stringent application integrity needs. SEUs are totally transparent to applications with no need for complex

software recovery schemes. The GPMs have both the through put and memory to host the required applications with ample growth margins.
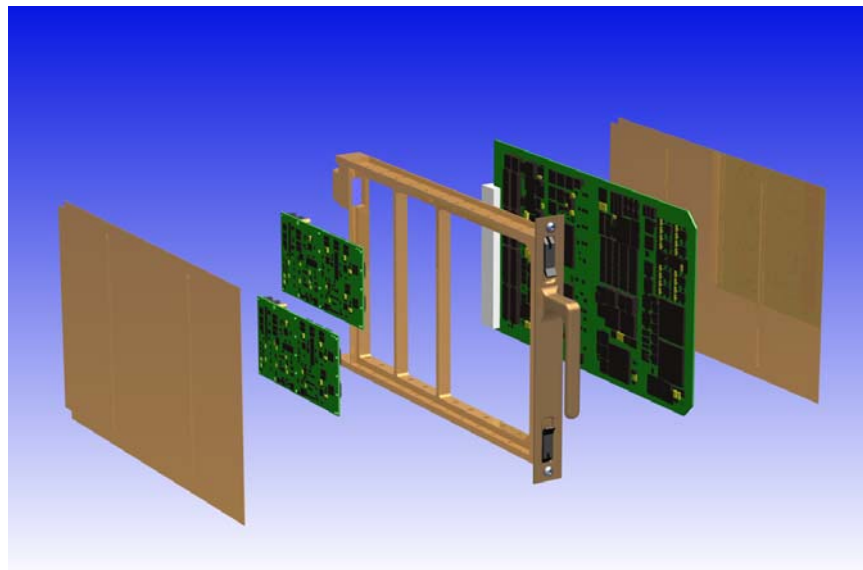
Figure 11.2. Illustration of the General Processing Module

The dual-redundant AFDX interface, capable of running at full 100 Mbps line rate provides the I/O communication needs for the GPM. All software and configuration files are on-board loadable using A615A load protocol.

To ease maintenance operations, the GPM is designed to be "hot swappable". Separate processor control and debug channels are provided to support the lab development environment as well as production.

Four GPMs are provided in the FDU CCS configuration to support the most stringent redundancy requirement for hosted functions [Sm04].

11.3.2 Common Data Network (CDN)

The CCS utilizes a Common Data Network (CDN) that is distributed and accessible throughout the aircraft as shown in Figure 11.3. The network utilizes a switched star topology where numerous peripherals are connected via fiber optic media to a series of switches which are in turn connected. The architecture resembles a Local Area Network (LAN) common in networks of PCs. The network can operate between 10 and 100 Mbps with a growth potential to 1 Gbps. Additionally, there are devices called Remote Data Concentrators (RDC) that collect analog, discrete, and serial digital interfaces.

At the core of the network communication backbone is the ARINC 664 compliant AFDX switch shown in Figure 11.4. The switch provides high integrity network connections for all CCS components and any application specific units that require high bandwidth communication. The AFDX network provides an interconnect and network protocol that is compliant with industry standard ARINC 664 part 7 and IEEE 802.3. Each switch provides 24 full duplex ports that are capable of routing data to support the full 100 Mbps line rate of each port. The switch ensures network integrity and bandwidth guarantees by policing of the network data flows, only allowing

routing for messages that comply to pre-configured addressing, size and frequency. The switch also records any occurrence of policing actions, providing the capability to query this data base to aid in fault isolation. All software and configuration files are on-board data loadable using the ARINC 615A data load. The network technology is a reuse of AFDX switches and end systems being developed and certified for the A380 program. The switch components are being repackaged into form factors appropriate for the 7E7. The tools to develop configuration files for the switches/end systems and analyze the network data flows for guaranteed min/max latencies are being reused as well. The AFDX network backbone is arranged in a dual/dual topology, providing redundant communication paths for both the right and left sides of the airplane [Sm04].
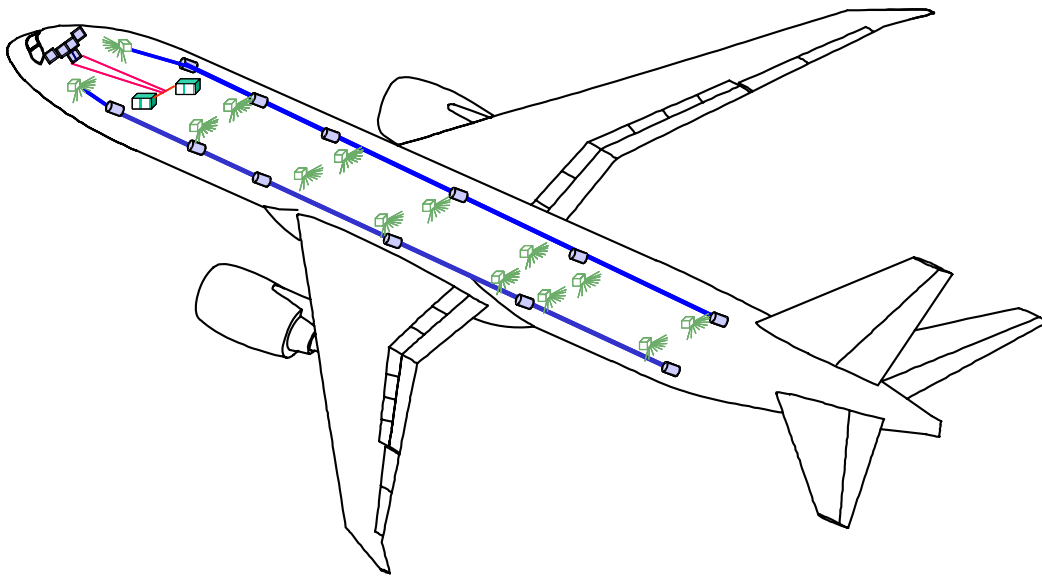
Figure 11.3. Illustration of aircraft with numerous Remote Data Concentrators along the fuselage for collecting information

11.3.3 Remote Data Concentrators (RDC)

The RDC (see Figure 11.5) provides interfacing and gateway services for both analog and legacy ARINC 429 digital busses. It is capable of interfacing up to 150 analog interfaces which may be composed of multiple electrical primitives. These interfaces can be converted and updated on the network at rates up to 200 Hz. Signal status such as for open/short detection and electrical range checks is provided as well. Likewise, legacy ARINC 429 digital buses can be gate-wayed to/from the network at rates up to 200 Hz. The RDC is designed to be conveniently positioned in the airplane to minimize wire length for connecting devices. As such, it is designed to be passively cooled and bolted to the airplane structure. The connectors are accessible from the top of the unit for quick installation and connection.

The RDC is designed to be highly configurable through the use of configuration files. These files map the actual signal connections to processing that is specific for the I/O type connected. The

files also specify the update rates and network data formats, basically establishing the gateway attributes for each connected interface.
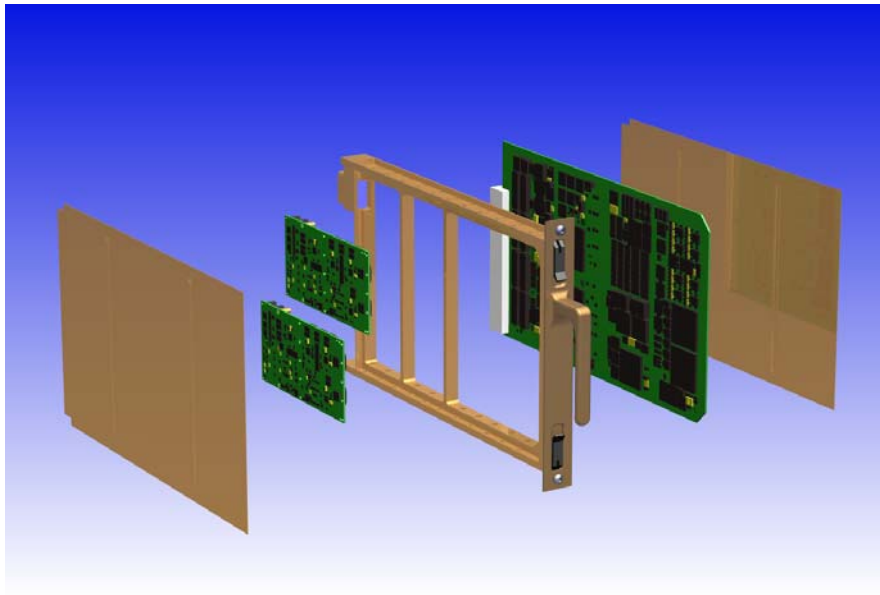
Figure 11.4. Illustration of the CCR AFDX Switch
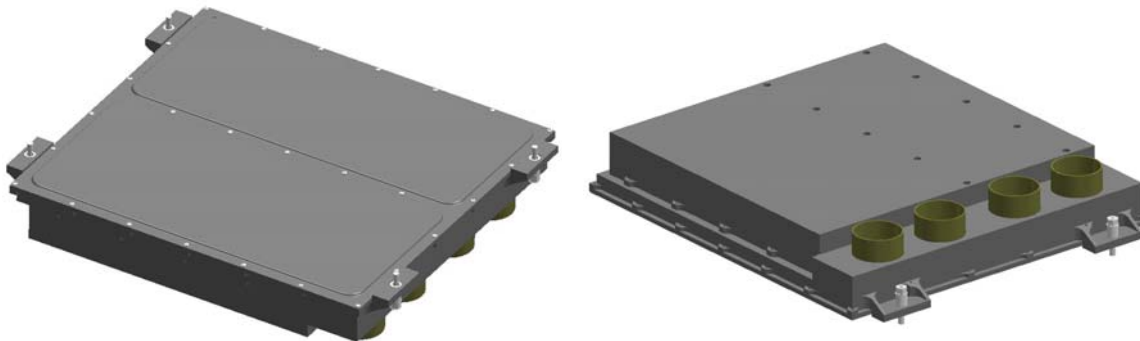
Figure 11.5. Remote Data Concentrators (RDC)

The RDC can store up to 32 pin-selectable configurations files allowing use of a single superset configuration file to be used across an application. This number of configuration files covers the unique FDU RDC configurations for the tier 1 airplanes [Sm04].

11.3.4 CCS Generic Architecture

The generic architecture for the Common Core System is illustrated in Figure 11.6. The architecture consists of dual CCR cabinets connected by the AFDX data bus. Each cabinet has

four General Processing Modules along with assorted Line Replaceable Modules (LRM). Externally, Line Replaceable Units that are compatible with the data bus can be connected directly to one of the AFDX switches.
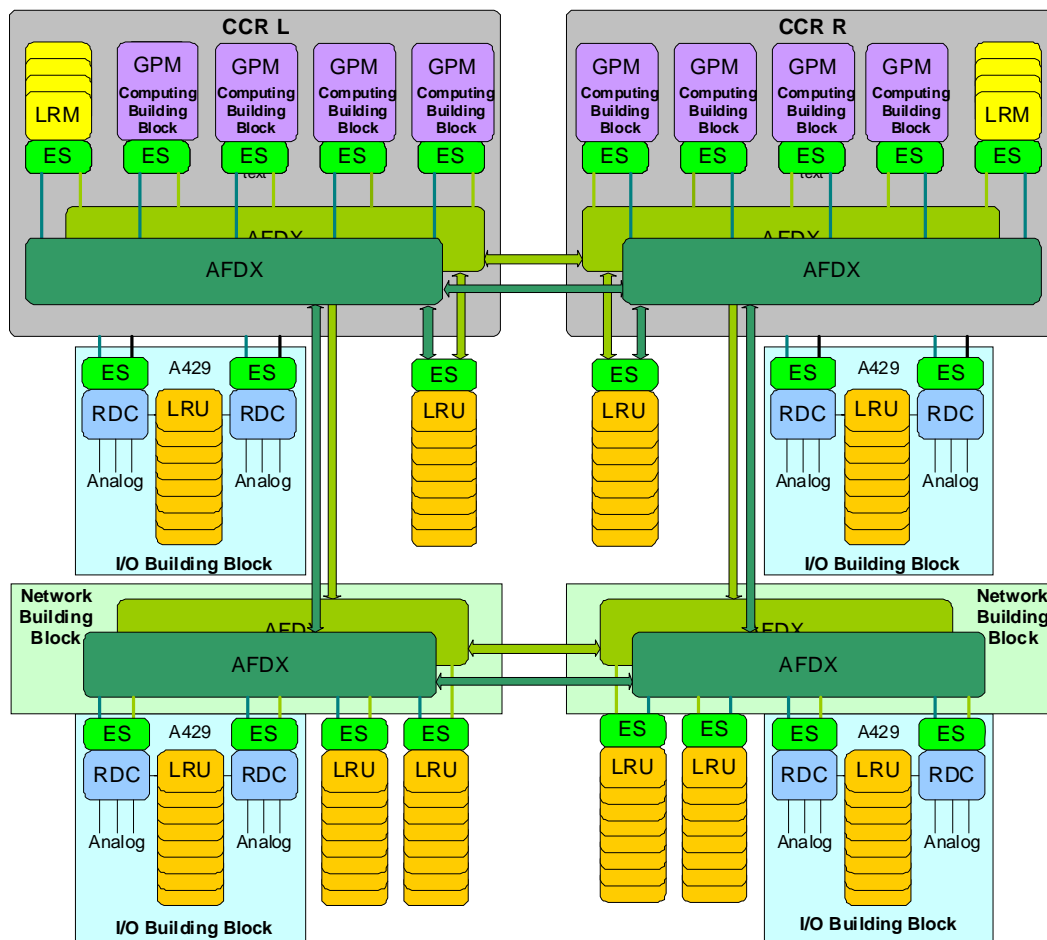
Figure 11.6. CCS Generic Architecture

Other units that have analog outputs or ARINC 429 outputs must be first connected to a Remote Data Concentrator (RDC) and then connected to a switch [Sm04].

12. Design Requirements, Guidelines, Standards and Certification

In the previous sections, we discuss the various digital avionics components and system architectures that exist or that are emerging in new aircraft. These have all been designed, developed and tested according to sets of requirements, design guidelines and standards, and rigorous certification processes established by the FAA. In the design of modern avionics components or systems, one has to consider the questions, in turn:

- What are the avionics system or component design requirements?
- What accepted guidelines should be followed in producing this design?
- What avionics design standards apply?
- What is the process followed to certify the component or system?

The aspects that address each of these questions are discussed in turn in the following sections.

12.1 Design Requirements

The first step in any design process is to define the customer requirements for the new product. Inherently, the designer must ask and answer: What is the reason for developing this new design? Is it an entirely new product based upon an entirely new concept or innovation, or does it address problems with or improve upon an older product because of one or more reasons? Proper requirements are the foundation for well-designed avionics. Whatever the sources of requirements, and whatever the methods used for their capture and refinement, an avionics designer must be able to demonstrate that a new system's requirements – performance, safety, maintenance, continued airworthiness, etc. – have been addressed comprehensively. There are detailed design requirements for every avionics component of an aircraft, and these are too numerous to include in this report. In the following, we describe the general characteristics of design requirements and then illustrate design requirements by describing those for a typical multi-modal digital avionics component – the cockpit display of traffic information (CDTI).

12.1.1 General Design Requirements

In terms of multi-modal digital avionics, consider as an example the requirements thinking that one would do in transitioning from use of fluidic-mechanical pneumatic gyros for attitude rate sensing to solid state electro-mechanical rate sensors because they are less expensive, more reliable, and easier to maintain. Some of the more common customer requirements in making such a switch are:

1. Safety. How does using this new component affect the safety of flight as compared to the component it replaces? This, in turn, requires that we understand what safe flight means and how it is measured, and then how this component affects that metric. For example, when we switch to solid state rate sensors, we are requiring that the functions it affects such as pilot displays, flight controls inputs, and warning devises that make use of attitude rate be more reliable and less prone to hard failures than with the older pneumatic devises.

2. <u>Mission</u>. Here the requirement might be that we wish to enhance or extend the mission of the aircraft beyond that which is possible with an older design. For example, use of the FMS improves the fuel burn performance of the aircraft enabling it to fly greater range or with larger payload. The FMS uses rate sensors as standard input devices for lateral and vertical steering. So a more reliable rate sensor equates to a more reliable FMS. Non-flight mission related metrics also included are ground turn around or start up time, lower maintenance effort, or lower training requirements.

3. <u>Life Cycle Costs</u>. The acquisition part of typical life cycle costs for avionics is 60% [SP00; Chapter 19]. Given that this is such a large part of the cost driver, the associated requirement might be that purchase, integration, and installation of our new rate sensor should be equal to or less than the similar costs of using the pneumatic device.

Customer requirements, in turn, transition into functional requirements for the component or system. Functions are typically broken into those to meet the overall mission (e.g., cargo capacity) or mission segment (e.g., climb performance, roll rate). These dictate the associated avionics functions and their requirements (e.g. provide heading with an accuracy of better that 0.3 deg.). These functional requirements, in turn, dictate component requirements such as measurement accuracy, range, noise content, reliability, repeatability, and availability.

12.1.2 CDTI Design Requirements Example

To illustrate the specific detail that can go into avionics component design requirements, this section provides an overview of one particular component – the CDTI system. The CDTI provides both navigation and surveillance information to enhance situational awareness and command and control information for facilitating flight efficiencies. The CDTI functions are first described; these lead to CDTI design requirements and associated system architecture that are also discussed.

12.1.2.1 CDTI System Functions

The CDTI system provides information about proximate other traffic relative to one's own aircraft. General CDTI functions can be classified into three categories identified in Figure 12.1:

- Data Fusion;
- Traffic Data Processing; and
- Human Interface.

Each of these three CDTI functions is now discussed.

12.1.2.1.1 <u>Data Fusion</u>

The data fusion function involves sensing, estimating, and combining traffic information. The traffic information consists of the state (position, velocity) of one's own aircraft (i.e., "ownship") from onboard sensors and surveillance information about other proximate aircraft received from a communication link. The types and properties of information necessary for CDTI functions depend upon the particular application that the CDTI will be used for.

The basic information needed consists of the current position of the proximate aircraft relative to ownship (e.g., range, bearing, altitude). Other useful information includes time, flight ID, relative aircraft speeds, horizontal and vertical tracks, and aircraft performance. Other data that will

affect alerting system thresholds include phase of flight, separation criteria, and the relationship to the intended landing runway [S99].

Important data fusion functions include the combination of different data sources to determine a single traffic datum, data error checking, and temporal extrapolation of the surveillance data. The combination of the different data sources takes into account the different content, accuracies, transmission times, and update rates of the different data sources.
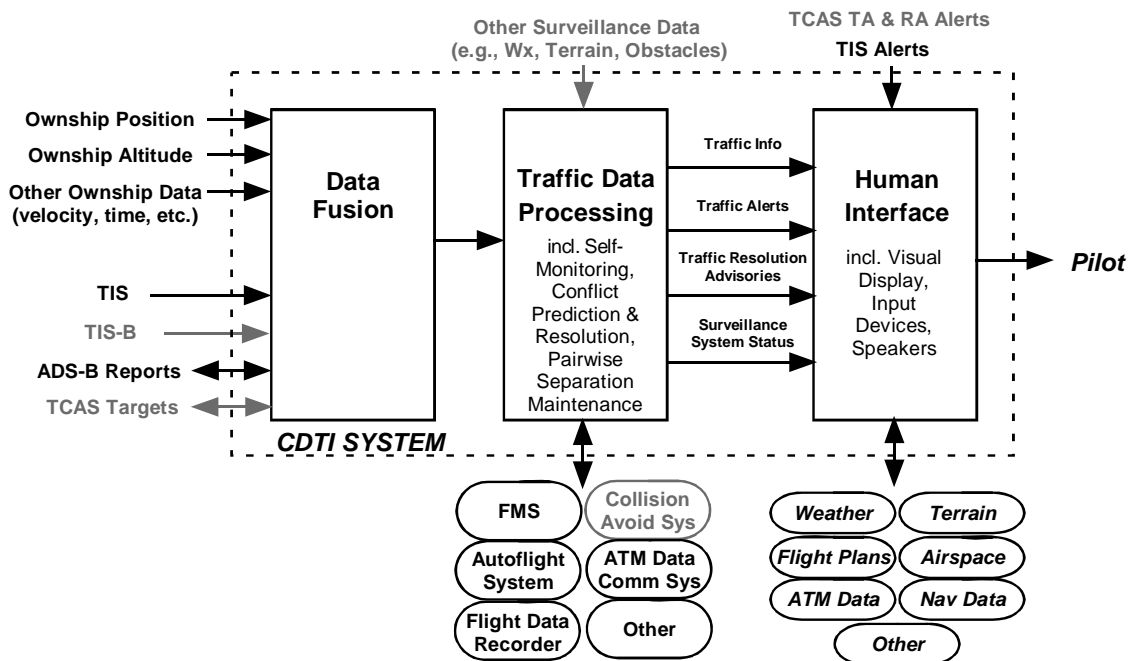
Figure 12.1. CDTI System Functional Diagram

12.1.2.1.2 Traffic Data Processing

The traffic data processing function consists of a number of sub-functions, depending upon the CDTI application. It includes a system self-monitoring/integrity checking function and the conversion of the sensed data into a format useful for the display interface. The self-monitoring function determines whether the sensed data is erroneous or the CDTI system has experienced some type of failure. The outputs of the self-monitoring function support pilot determination of the suitability of the CDTI data for use in various applications. Other data processing functions include the generation of derivative data (e.g., pairwise separations, closure rates), conflict prediction, traffic alerting, and conflict resolution advisory generation.

The output includes traffic information (e.g., relative aircraft locations and velocity), surveillance system status (e.g., the results of the self-monitoring function), traffic alerts (e.g., both for an impending conflict and when the conflict is over) and resolution advisories (e.g., open-loop command guidance such as "no-go" zones or suggested conflict avoidance maneuvers, or closed-loop command guidance such as flight director bars on the primary flight display).

12.1.2.1.3 Human Interface

The human interface presents the relevant traffic information to the pilot. This interface typically consists of a visual graphical display (e.g., an electronic plan view display) combined with an aural display (e.g., a cockpit audio system), and the appropriate pilot input devices (incl. manual or voice-activated controls). The visual display may accommodate the simultaneous viewing of traffic data with other information including aids to navigation, weather, terrain, or others.

12.1.2.2 Traffic Information Requirements

The previous functions have the following requirements.

12.1.2.2.1 Traffic Information and Potential Conflicts Display

A graphical real-time display of traffic and traffic conflicts is required with the performance specifications shown in Table 12.1.

Table 12.1. CDTI Performance Specifications

System Parameter	Required Performance
Display Range	5-100 nmi
Traffic Position Accuracy	0.3 nmi horizontal 500 ft altitude 5 deg heading
Visual and/or Aural Alert Latency	< 4 seconds
Visual and/or Aural Alert Time-to-Closest-Point-of-Approach	2 minutes

The purposes for this display are to provide traffic information for guidance, planning and overall situational awareness and timely conflict avoidance alerts. Information includes relative traffic positions with ownship and other aircraft trend vectors, and an alert-triggered highlighting of either or all of conflicting traffic, 'no go' or collision zones, and advisory vectors.

12.1.2.2.2 Traffic Alerts

 "Traffic Alerts" stipulates that an aural and graphical alerting system is required. This traffic alerting system is used to provide the pilot with (a) visual aircraft proximity cautions; (b) tone and/or voice and visual aircraft collision warnings at two minutes time-to-unsafe-separation; and (c) annunciation of when the CDTI system is not working or functioning properly.

12.1.2.2.3 Surveillance and Enhanced Situational Awareness

 "Secondary Surveillance Radar (SSR)", "Traffic Information Service (TIS)", and "ADS-B" stipulate the aircraft requirement of being equipped with at least a Mode C Transponder as well as to able to receive TIS and ADS-B information. Also, the aircraft broadcast their position and heading in compliance with emerging ADS-B standards.

12.1.2.2.4 Selected CDTI Functional Requirements

Additional "minimum" and "enhanced" CDTI requirements are summarized Table 12.2.

Table 12.2. Selected CDTI Functional Requirements

	Notes
Minimum Requirements	
Position Information	Higher accuracy needed for ground and terminal airspace ops than en route
Velocity Information	Bearing, speed, and rate of climb/descent
Ability to Handle Non-Radar Coverage	
Traffic Advisory Information	
Traffic Conflict Warning	
Information Aiding Conflict Resolution	Defined as "situational awareness information" to enable the pilot to determine and to perform conflict resolution"
3 Separate 2-D Display Formats	Taxi Map, Proximate Traffic Display (based on existing nav or weather map or TCAS-1 based), Intruder Alert Display (TCAS-1 based)
Display Declutter	Pilot-selectable filters based on altitude, distance, or time to closest point of approach
Traffic Database	Stores position, velocity, and intent data for up to 100 aircraft
Display Controls	Include North-Up/Track-Up, Range, and Scale
Traffic Display-Nav Display Interaction	Nav display will include compass rose, ownship symbol with heading, and range rings
Enhanced Requirements	
Trend Vectors	
Intent Information	
Automated Resolution Advisories	

12.1.2.3 CDTI System Architecture

12.1.2.3.1 Functional Architecture

In a CDTI functional architecture derived from [RTCA243], Ownship data are typically represented by Ownship position, altitude, velocity, time, and other data required for ADS-B reports [RTCA242]. These Ownship data are nominally intended to be provided by the Global Navigation Satellite System (GNSS) and barometric altimeters, but could be enhanced by differential GPS (DGPS) corrections or the planned Wide Area Augmentation System (WAAS) or provided by other backup sensors such as Distance Measuring Equipment (DME) equipment.

Surveillance data in Figure 12.2 are represented by the receipt of TIS, TIS-Broadcast (TIS-B) within terminal Secondary Surveillance Radar (SSR) coverage areas and the transmission/receipt of ADS-B reports and TCAS target information. These surveillance data are sent with the Ownship data to the traffic data processing unit.

This traffic data processing unit interfaces with other onboard systems including the Flight Management System (FMS), Collision Avoidance System (typically TCAS-II), Auto-flight system, Air Traffic Management (ATM) communication unit, and Flight Data Recorder. This data processing unit accepts other surveillance information on potential hazards such as adverse weather, terrain, and obstacles in order to take them into account in the resolution advisory process.

Finally, the traffic information, alerts, resolution advisories, and surveillance system status information are combined with TIS alerts, TCAS Traffic Alerts (TAs) and Resolution Advisories (RAs) and appropriately communicated to the pilot through the CDTI human interface. This human interface will consist of a visual display, an audio display, and the appropriate input devices. The visual display part of the human interface provides a medium that integrates the traffic information with other information such as weather, terrain, flight plans, airspace, ATM data, and navigational data.

12.1.2.3.2 System Architecture

The functional architecture translates into the system architecture shown in Figure 12.2.

The primary pieces of onboard hardware needed to mechanize the CDTI system include:

- Global Positioning System (GPS) receivers/processors for sensing aircraft position and geometric altitude
- GPS receivers capable of receiving DGPS correction signals for precision position sensing when the aircraft is on the airport surface
- Barometric Altimeter to sense pressure altitude
- Level 2 Mode S transponder with the capability to receive TIS and receive/transmit ADS-B reports
- Flight Computer with software to provide the data fusion and traffic data processing functions
- Audio System to provide the CDTI aural alerts, and
- CDTI visual display to provide traffic information and CDTI visual alerts.

This system interfaces with other aircraft subsystems such as the FMS, Flight Control (incl. Auto-flight) system, ATM data communication system, and Flight Data Recorder. Also, the CDTI display is displays other safety-critical information such as terrain and obstacles within the alert zone and dangerous weather regions such as wind shear or microburst activity. The CDTI is envisioned to be one layer of the MFD that can also display flight plans, airspace boundaries, ATM data, navaids, geopolitical boundaries, and airports.

12.2 Design Guidelines

Another important aspect of avionics design is attention paid to the design guidelines, or philosophies, that have been established over years of development by a particular manufacturer or that of a particular customer, especially related to human interface with the automation functions that avionics systems provide to the flight deck. In the following, we first discuss general design guidelines followed by a brief description of published guidelines for electronic airborne (avionics) hardware and the CDTI.
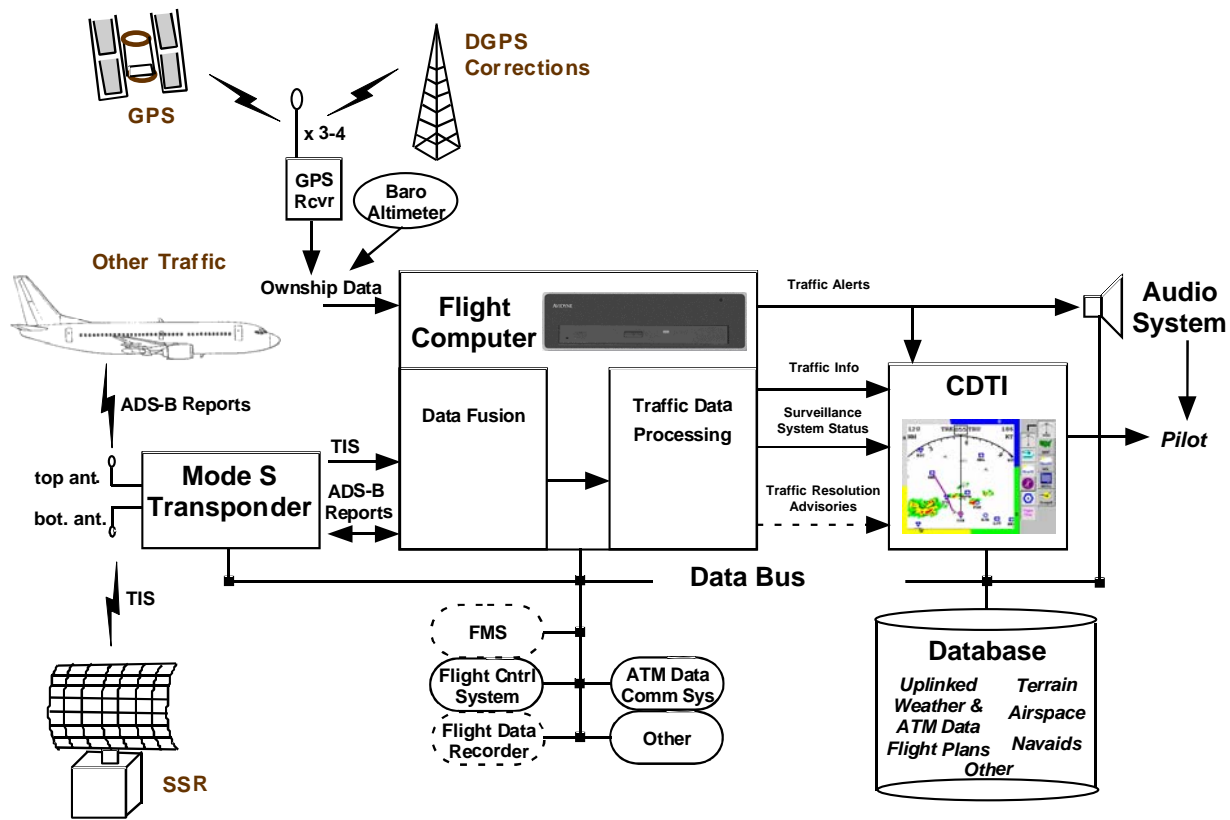
Figure 12.2. CDTI System Architecture

12.2.1 General Guidelines

Abbott [SP00; Chapter 9] compares the flight deck design philosophies of Airbus and Boeing as follows:

Airbus:

1. Automation must not reduce overall aircraft reliability; it should enhance aircraft and systems safety, efficiency and economy;

2. Automation must not lead the aircraft out of the safe envelope and it should maintain the aircraft within the normal flight envelope;

3. Automation should allow the operator to use the safe flight envelope to its full extent, should this be necessary due to extraordinary circumstances;

4. Within the normal flight envelope, the automation must not work against operator inputs, except when absolutely necessary for safety.

Boeing:

1. The pilot is the final authority for the operation of the airplane;

2. Both crew members are ultimately responsible for the safe conduct of the flight;

3. Flight crew tasks, in order of priority, are safety, passenger comfort, and efficiency;

4. Design for crew operations based on pilot's past training and operational experience

5. Design systems to be error tolerant;

6. The hierarchy of design alternatives is simplicity, redundancy, and automation;

7. Apply automation as a tool to aid, not replace, the pilot;

8. Address fundamental human strengths, limitations, and individual differences – for both normal and non-normal operations;

9. Use new technologies and functional capabilities only when:

    a. They result in clear and distinct operational or efficiency advantages; and

    b. There is no adverse effect to the human-machine interface.

Here we see the contrast between the Airbus philosophy of using hard limits of envelope protection vs. the soft limits of the Boeing philosophy where the pilot has greater authority.

Another general example of customer-based design guidelines might be that all flight decks, regardless of aircraft type, look alike with the same control feel and responsiveness. This would enable the flight crew to train for a particular aircraft type but be able to quickly adapt to another type. It would also reduce training time and cost.

12.2.2 Avionics Hardware Development Guidelines

Reference RTCA/DO-254 [RTCA254] provides design assurance guidance for developing airborne electronic hardware. This is a very important design guidance document for digital avionics, and it consists of a detailed summary of best practices by the engineering organizations from international aviation manufacturers. Its intention is to provide this guidance for the development of airborne electronic hardware such that it safely performs its intended function in its specified environments. Document purposes are:

1. Define hardware design assurance objectives;

2. Describe objectives bases to help ensure correct interpretation of the guidance;

3. Provide descriptions of the objectives to allow the development of means of compliance with the guidance;

4. Provide guidance for design assurance activities to meet the objectives; and

5. Allow flexibility in choice of processes necessary to meet the objectives

The document recommends the activities that should be performed in order to meet design assurance objectives.

The guidance is applicable to the following hardware items:

1. Line Replaceable Units (LRUs)

2. Circuit board assemblies

3. Custom micro-coded components such as Application Specific Integrated Circuits (ASICs) and Programmable Logic Devices (PLDs)

4. Integrated technology components, such as hybrids and multi-chip modules

5. Commercial-off-the-shelf (COTS) components

Input to this process includes use of system requirements, Federal Air Regulation (FAR) advisory material, system development guidance, safety assessment guidance, environmental qualification test guidance materials, and other development constraints. The document then describes in turn:

1. System aspects of hardware design assurance – Hardware design assurance begins at the system level with the allocation of system functions to hardware and the assignment of their corresponding system development assurance levels. This includes a description of the information flow from system development process to hardware design life cycle process, hardware design life cycle process to system development process, and hardware design life cycle process to software design life cycle process. The functional hazard assessment (FHA) and system safety assessment (SSA) processes are also described.

2. Hardware design life cycle:
   a. Planning process – Defines the means by which the functional and airworthiness requirements are converted into a hardware item with an acceptable amount of evidence of assurance that the item will safely perform its intended functions;
   b. Design process –Produces a hardware item that fulfills the requirements allocated to hardware from the system requirements. The five major design processes include requirements capture, conceptual design, detailed design, implementation, and production transition;
   c. Validation and verification process –Provides assurance that the hardware item derived requirements are correct and complete with respect to system requirements allocated to the hardware item;
   d. Configuration management process – Provides the ability to consistently replicate the configuration item, regenerate the information if necessary and modify the configuration item in a controlled fashion if modification is necessary;
   e. Process assurance – Ensures that the life cycle process objectives are met and activities have been completed as outline in plans or that deviations have been addressed;
   f. Certification liaison process – Establishes communication and understanding between the applicant and the certification authority throughout the hardware design life cycle to assist in the certification process.

3. Hardware design life cycle data – This describes the hardware design life cycle data items that may be produced during the design process for providing evidence of design assurance and compliance with certification requirements.

Other consideration material including that for Level A (those with catastrophic failure condition classification) and Level B (hazardous/ severe-major failure condition classification) functions is also presented in this key document. These are described further in the next section.

12.2.3 Avionics Software Development Guidelines

RTCA/DO-178B [RT178B] presents the guidelines for software development that are generally used for certification of new avionics. These guidelines are specifically oriented to ensure levels of software performance consistent with achieving flight safety at an agreed upon level. More on DO-178B with respect to certification is presented in Section 13.2.4.

The DO-178B system safety assessment process determines and categorizes the failure conditions of the system. Within the system safety assessment process, an analysis of the system design components defines safety related requirements that specify the desired immunity from, and system responses to, these component failure conditions. These requirements are defined for hardware and software to preclude or limit the effects of faults, and may provide for fault

detection methods and fault tolerance. As decisions are being made during the hardware design process and software development processes, the system safety assessment process analyzes the resulting system design to verify that it satisfies the safety-related requirements.

The system safety assessment process also determines the impact of the software design and implementation on system safety using information provided by the software life cycle processes. This information includes fault containment boundaries, software requirements, software architecture, and error sources that may have been detected or eliminated through software architecture or by the use of tools or by other methods used in the software design process. Traceability between system requirements and software design data is important to the system safety assessment process.

DO-178B defines five particular failure conditions and the software level of certification (A-E) that must be achieved to attenuate and reduce to very low probabilities that such failure conditions would occur; these are listed in Table 12.3. The software level of certification implies the level of effort required to show compliance with certification requirements for the failure condition category. Note that in Table 12.3 , the effect of the failure condition for levels B-E is as applied to the safety of the flight crew and the occupants of the aircraft.

Table 12.3. Software Failure Condition Categorization and Corresponding Software Level Definition [RTCA178]

Failure Condition	Effect of Failure Condition	Software Level	Effect of Anomalous Behavior of Software
Catastrophic	Would prevent continued safe flight and landing	A	Would cause or contribute to a failure of system function resulting in a catastrophic failure condition for aircraft
Hazardous / Severe-Major	Would reduce the capability of the aircraft or the crew to cope with adverse operating conditions to the extent that there would be: 1. a large reduction in safety margins or functional capabilities 2. physical distress or higher workload such that the flight crew could not be relied on to perform their tasks accurately or completely 3. adverse effects on occupants including serious or potentially fatal injuries to a small number of those occupants	B	Would cause or contribute to a failure of system function resulting in a hazardous / severe-major failure condition for the aircraft
Major	Would reduce the capability of the aircraft or the ability of the crew to cope with adverse operating conditions to the extent that there would be a significant reduction in safety margins or functional capabilities, a significant increase in crew workload or in conditions impairing crew efficiency, or discomfort to occupants, possibly including	C	Would cause or contribute to a failure of system function resulting in a major failure condition for the aircraft.

	injuries.		
Minor	Would not significantly reduce aircraft safety, and which would involve crew actions that are well within their capabilities. Minor failure conditions may include a slight reduction in safety margins or functional capabilities, a slight increase in crew workload, such as routine flight plan changes, or some inconvenience to occupants.	D	Would cause or contribute to a failure of system function resulting in a minor failure condition for the aircraft.
No Effect	Which do not affect the operational capability of the aircraft or increase crew workload	E	Would cause or contribute to a failure of system function with no effect on aircraft operational capability or pilot workload.

12.2.4 CDTI Development Guidelines Example

Two ongoing aviation industry groups, RTCA SC-186 and SAE G-10, have generated guidelines for CDTI system design [RTCA243] [S99]. These cover the categories of CDTI design objectives, near-term CDTI applications, surveillance data processing, CDTI displays, CDTI controls, and CDTI-Flight System integration.

12.2.4.1 CDTI Design Objectives

SAE G-10's [S99] recommends a number of high-level CDTI design objectives. These basic design objectives include:

1. The minimization of pilot CDTI workload through (as described in [ARP571]):
   - o Simplifying operations
   - o Facilitating error-free operations
   - o Maximizing flight crew traffic awareness
   - o Minimizing head-down time
   - o Minimizing missed alerts and false alarms
2. The compatibility of CDTI system operation with pilot mental and visual models
3. The design of the CDTI system to generate pilot confidence in its operational integrity

Since affordability concerns will tend to drive CDTI systems towards providing 2-D plan view head-down displays (as opposed to head-up displays), it is imperative that the CDTI system be designed to impact as minimally as possible the pilot's through-the-windshield traffic scan in visual meteorological conditions (VMC).

12.2.4.2 Near-Term CDTI Applications

Out of the many potential CDTI-related applications proposed in [RTCA242], RTCA SC-186 focused on a few applications identified as being the most near-term [RTCA243] [MCD97]. The SC-186 work focused on determining the Minimum Operational Performance Specifications (MOPS) for three near-term CDTI applications: "Aid to Visual Acquisition", "Enhanced Visual

Approach", and "Enhanced Oceanic/Remote Procedures" [RTMO98]. These three applications map to the general ADS-B application categories and specific applications shown in Table 12.4. Further-out CDTI applications such as those involving pilot self-separation or flight path de-confliction planning are considered far-term CDTI applications and as such are considered after analyzing the near-term CDTI applications.

Table 12.4. Near-term CDTI Application Relationships to General and Specific ADS-B Applications

Near-Term CDTI Application [RTMO98]	General ADS-B Application [RTCA242]	Specific ADS-B Applications [RTCA242:Appendix D]
Aid to Visual Acquisition	Aid to Visual Acquisition	• Enhanced Visual Acquisition of Other Traffic for "See and Avoid" (D.1.19)
Enhanced Visual Approaches	Conflict Avoidance and Collision Avoidance	• Enhanced Visual Approaches (D.1.10)
Enhanced Oceanic/Remote Procedures	Conflict Avoidance and Collision Avoidance	• In-Trail Climb and In-Trail Descent in Oceanic, En Route, and Remote Non-Radar Airspace (D.1.1) • Lead Climb and Lead Descent in Oceanic, En Route, and Remote Non-Radar Airspace (D.1.2)

12.2.4.3 Surveillance Data Processing

Both RTCA SC-186 and SAE G-10 provide guidance on suggested surveillance data processing functions [RTMO98] [S99]. These cover the CDTI functions previously described as the Data Fusion and Traffic Data Processing functions. They include:

- Data error checking;
- Fusing surveillance (Ownship and target aircraft) data from different sources to provide a single datum per aircraft. Data fusion addresses the handling of data with differing content, accuracies, transmission times, and update rates;
- Temporal extrapolation or "coasting" of surveillance data;
- Transformation of the surveillance data into the CDTI display coordinates;
- Calculation of necessary derivative quantities (e.g., closure rates, ground speeds ground track vectors);
- Determination of necessary traffic alerts. This includes filtering traffic based on designated threat criteria (e.g., range, altitude, horizontal miss distance, vertical miss

distance, and time-to-CPA) and priority, and fusion of onboard traffic alert processing with received alert information (e.g., TIS alerts);

- Suppression of traffic data, symbol, and alert level "cycling"; and
- Determination and communication of data source failures.

In general, the RTCA SC-186 and SAE G-10 groups focused on the data fusion and processing of Ownship data with surveillance data from TIS, TIS-B, ADS-B, and TCAS. The expected use of TIS and ADS-B surveillance data requires the data fusion and processing of the information shown in Table 12.5. TIS information provides request/reply surveillance of all ATCRBS-equipped target aircraft in Mode S sensor surveillance range that are within 5 nmi range and 1200 ft altitude. ADS-B information provides broadcast surveillance of all ADS-B-equipped aircraft, independent of radar coverage and airspace domain (i.e., ADS-B data are reliable on the airport surface, and at low and high altitudes).

Table 12.5. ADS-B and TIS Surveillance Information [RTCA243]

Parameter	ADS-B[*]	TIS[**]
Target position information	- latitude - longitude - altitude	- relative range - relative altitude - bearing
Nominal range (nmi)	10-120[1]	5[2]
Nominal received update period (sec)	3 in air, 1.5 on surface[3]	4-12[4]
Target aircraft equipment required	ADS-B transmitter	Mode A/C or Mode S transponder[5]
Additional target information	- call sign - aircraft category - address - class code - velocity - acceleration (on surface)[6] - NUC (position and velocity)	- vertical rate indication (climbing or descending) - traffic advisory status (TCAS I-type)

[*]More details can be found in the ADS-B MASPS. [RTCA242]

[**]More details can be found in the TIS MOPS. [TM97].

[1]The minimum range for the least capable ADS-B system is 10 nmi; a range of 50-100 nmi is expected for most ADS-B systems

[2]TIS provides traffic information and traffic alerts for targets within 5 nmi and 1200 ft of ownship. For traffic outside this range, only a traffic alerting capability is provided. The TIS message indicates range up to 7 nmi and can indicate if the target is beyond 7 nmi.

⁴The TIS update period is dependent on the scan rate of the Mode S sensor operating the service.

⁵TIS may potentially include targets detected from primary radar.

⁶[RTCA242] suggests that a discrete turn variable signalling "not turning", "turning right" or "turning left" would be transmitted and not a continuous value of the acceleration.

ADS-B surveillance information is only available from ADS-B equipped aircraft. This is not so much of a concern for TIS information since significant portions of US airspace (e.g., Class A airspace and airspace within 30 nmi Mode C "veils" around major US airports) require Mode C transponders and 85% of all GA aircraft are properly equipped.

Unlike ADS-B information which is independent of airspace coverage, TIS information is only available for airspace that will be covered by Mode S secondary surveillance radars. Therefore, TIS information will only be available in 143 high-density US CONUS terminal airspaces. Also, unlike ADS-B which has high levels of information accuracy, TIS has accuracy problems especially in the cases of bearing information for targets at close relative ranges and at low pattern altitudes. In fact, TIS information accuracy is low enough that TIS information is specified to be only of an advisory nature and only suitable for VFR flights. Finally, detailed TIS position information is only provided for aircraft within relative ranges of 5 nmi, whereas ADS-B surveillance information is good for relative ranges of at least 10 nmi, but more likely at 50-100 nmi.

12.2.4.4 Display Considerations

In addition to guidance on surveillance data processing, the RTCA SC-186 and SAE G-10 groups have generated a significant amount of display guidance. [RTCA243] [RTMO98] and [S99] describe more general guidance with a slant towards human factors-related recommendations (e.g., display ergonomics, color, and symbology) and [RTMO98] describes more specific guidance (although tied to the 3 near-term CDTI applications discussed before) with a slant towards technical recommendations (e.g., display information required).

12.2.4.4.1 Display Design

The SAE G-10 group designated that display design should be consistent with aviation industry-accepted practices and standards such as:

1. SAE Aerospace Recommended Practice, ARP 4102/4, *Flight Deck Alerting System (FAS),* July 1988. [ARP4104]

2. SAE Aerospace Standard, AS 8034, *Minimum Performance Standard for Airborne Multipurpose Electronic Displays,* December 30, 1982. [AS8034]

3. SAE Aerospace Recommended Practice, ARP 4032*, Human Engineering Considerations in the Application of Color to Electronic Aircraft Displays,* April 4, 1988. [ARP 4032]

4. SAE Aerospace Recommended Practice, ARP 4102/7, *Electronic Displays,* July 1988. [ARP 4107]

5. SAE Aerospace Recommended Practice, ARP 4102, *Flight Deck Panels, Controls, and Displays,* July 1988. [ARP 4102]

6. SAE Aerospace Recommended Practice, ARP 1093, *Numeral, Letter, and Symbol Dimensions for Aircraft Instrument Displays,* July 1988. [ARP 1093]

12.2.4.4.2 Display Information

Specific display guidelines have been generated by the RTCA SC-186 for the three near-term CDTI applications that they have focused on so far (see Table 12.6) [RTMO98]. These display guidelines include the specification of display information and features that are required, desirable, or not required.

Table 12.6. CDTI Display Requirements for Near-term CDTI Applications

	Aid to Visual Acquisition [RTMO98]	Enhanced Visual Approach [RTMO98]	Enhanced Oceanic/Remote Procedures [RTMO98]
Target Information			
Ownship symbol	R	R	R
Target aircraft symbol	R	R	R
Target aircraft altitude (barometric)	R	R	R
Target aircraft relative bearing	R	R	R
Target aircraft relative range	R	R	R
Call sign	D	R	R
Closure rate	D	R[1]	R[1]
Ground speed	D	R[1]	R[1]
Ground track	D	R	D
Vertical rate	D	D	N/R
Flight Plan Intent data	N/R	N/R	N/R
Display Features			
Target highlighting	D	R	R
Extended display range	N/R	N/R	R

Range reference	D	D	D
Compass rose	N/R	N/R	N/R
Taxi map	N/R	N/R	N/R
Terrain/obstacle/ adverse weather within alert zone	N/R	N/R	N/R
Traffic alerting	D	D	N/R
Resolution advisories	N/R	N/R	N/R

R=Required

D=Desireable

N/R= Not Required

R^1 = Either closure rate or ground speed, but not both.

12.2.4.4.3 Display Alerting

Current aviation industry recommendations on traffic information display and alerting schemes include those previously designed into current TIS [TMO], TCAS-I [T1MO], and TCAS-II [T2MO] display and alerting systems. The CAA CDTI design is certified for use as an "Aid to Visual Acquisition" and has been thoroughly researched and tested by NASA, FAA, MITRE, and MIT Lincoln Laboratory human factors researchers and CDTI experts.

For the purposes of alerting the pilot, the aviation industry recommends the use of both visual display alerts as well as aural (either voice or tonal) alerts. These alerts should assist the pilot in knowing both when a possible conflict becomes a threat, as well as when it ceases being a threat.

CDTI traffic alert colors should be consistent with previously adopted standards for TCAS and flight alerting systems. These standards include the use of red for situations requiring immediate action, and the use of yellow/amber for situations requiring immediate awareness and possible future action. Also, when use of color is important, it should be used in combination with another variable such as shape [S99].

12.2.4.4.4 Resolution Advisories

Resolution advisory recommendations were determined to be outside the scope of [RTMO98], but [S99] suggests a range of options including: (a) a caution (e.g., "Traffic"); (b) an open-loop command (e.g., "Climb"); or (c) closed-loop command guidance (e.g., flight director bars). In the case of the third resolution advisory option, [S99] suggests the possibility of resolution command guidance being provided through any or all of the following options:

- Flight Director bars on the Primary Flight Display (PFD), Electronic Attitude Director Indicator (EADI), or Attitude Director Indicator (ADI);
- Fly to/away from symbology on the Vertical Speed Indicator;
- Turn director or commanded path on the Electronic Horizontal Situation Indicator; and
- Vertical Flight Path Director on a Profile View Display.

In addition to the command guidance, potential utility is also expected in the display of 'non-transgression zones'.

12.2.4.4.5 Other Considerations

On the subject of expected conflict resolution maneuvers, [S99] reiterated the results of previous display research that has shown that plan view CDTI displays will tend to bias the observer towards horizontal resolution maneuvers.

The CDTI will need to have an automatic ability to monitor the integrity of the CDTI surveillance system. For such a control, RTCA SC-186 recommends the annunciation of five specific CDTI system states [RTMO98]:

1. Turned off
2. Failed
3. Enabled and functioning normally
4. Enabled and functioning in an off-normal state
5. Self-test/Built in test

Additionally, it would be desirable for the system to detect and display the absence of power, inadequate or invalid Ownship data, and inadequate or invalid surveillance data. If proper status information is displayed, the CDTI might still be usable in a degraded system state for certain CDTI applications.

12.2.4.5 Control Considerations

As RTCA SC-186 and SAE G-10 groups point out, there are a number of recommended controls that would be very useful to a pilot using a CDTI. These key controls include:

- Self-Test – This control would allow the pilot to test the status of the CDTI surveillance system.
- Display Orientation – Past research has shown advantages to having both a "heading-up" and a "north-up" display orientation to the CDTI display. [S99] The SAE G-10 recommends that the option exist for the pilot to choose between the orientations.
- Display Range – This would allow the pilot to select the proper range for display of other proximate traffic. Previous human factors studies have shown a desire by pilots to change CDTI display ranges based on a desire to manage the density of air traffic data on the display [LMM97].
- Target Selection – This control would allow the pilot to see more detailed information about a specific aircraft. This would be especially important for desirable target information that might be too detailed to be shown in the nominal display state for all aircraft (i.e., it would cause too much clutter). This would be especially important for pilot access of the full ADS-B target information set. Note: A suggested way of handling the display of the additional highlighted target data is the arrangement of the display to show spatial air traffic relationships in the center of the display and control and detailed data around the outer edges.
- Display De-clutter – This control would allow the pilot to suppress or remove information as well as the ability to change the display's organization. This control would be very important in situations such as flight on or near the airport surface where a

significant density of aircraft would be displayed. As [S99] recommends, this control should be manual to enhance pilot awareness and automatic de-cluttering should be avoided whenever possible.

- Lighting/Brightness – This control would govern the display brightness to ensure adequate lighting under the range of experienced ambient lighting conditions. [S99] mentions that this control may be either manual or automatic.

- Altitude Dimension – This control would allow the pilot to switch altitudes displayed on the CDTI between absolute altitude and altitude relative to Ownship.

[S99] suggests that these controls be designed in a way to minimize pilot workload. The first key control is the Self-Test control.

12.2.4.6 Integration Considerations

As RTCA SC-186 and SAE G-10 groups recommend, the smooth and efficient integration of the CDTI system with other aircraft systems is a requirement. [S99] suggests that the CDTI design be consistent with other aircraft systems' operating philosophy, standardization, automation, color, symbology, and alerting systems. A useful reference that provides guidance for integration of CDTI systems is [AC25]. The CDTI system needs to ensure its proper integration with other flight systems, displays, alerts, and overall operational requirements.

CDTI flight system integration involves the proper integration of the CDTI with other relevant aircraft flight systems such as the flight management system, the auto-flight system, the flight director, the data communication system, the weather and terrain warning systems, and the flight data recorder. At the very least, this CDTI integration should not degrade the performance of the CDTI or the other systems (e.g., terrain avoidance guidance) integrated. [RTMO98]

Also, the CDTI should be "properly" integrated with other relevant displays such as the primary flight display, navigation display, weather display, and data communication displays. In the case of a CDTI MFD, there is at least a need for an indication of the MFD display mode or status.

The CDTI alerting system needs to be integrated with other onboard aircraft alerting systems. The SAE G-10 recommends that these alerting systems and their integration follow the guidelines expressed in [FAA81]. Therefore, visual and aural prioritization of any existing traffic alerts with other impending aircraft alerts (e.g., of weather, SUA, obstacle, terrain, ATM message, and flight envelope limit) need to be determined and properly defined.

One last important CDTI integration issue is the CDTI's integration into the nominal flight operational requirements. If use of the CDTI results in a new allocation of responsibilities and functions among the pilots, controllers, and automation, this new allocation should not adversely affect the performance of existing tasks. [S99] This will become a critical issue in future cases in which pilots use CDTI to support pilot self-separation in IFR conditions.

12.3 Design Standards

There are several important standards that come into play in design of digital avionics. These have been established by the airlines and the FAA so that avionics manufacturers can build products that are consistent in performance and so that one manufacturer's avionics components can be readily intermingled with the avionics components of other manufacturers. For example,

the Collins radio or Honeywell GPS receiver works with the Smiths FMS. The following describes some of the more important avionics standards that have been established.

12.3.1 Digital Data Buses

Digital data buses provide the necessary onboard digital communications among the avionics components comprising the overall system. Data buses use standardized physical and electrical interfaces to send their data from one avionics component to other avionics components as required for their normal functions. There are four digital data bus standards of interest – MIL-STD-1553, ARINC 429, ARINC 629, and Commercial Standard Digital Bus (CSDB).

12.3.1.1 MIL-STD-1553.

This data bus standard defines the term Time Division Multiplexing (TDM) as the transmission of information from several signal sources through one communications system with different signal samples staggered in time to form a composite pulse train. This means that data can be transferred between multiple avionics units over a single transmission media, with the communications between the different avionics boxes taking place at different moments in time. The 1553 standard defines certain aspects regarding the design of the data bus system and the black boxes to which the data bus is connected. The standard defines the following four hardware elements:

1. Transmission media is defined as a twisted shielded pair transmission line consisting of the main bus and a number of stubs. The characteristics of both the main bus and the stubs are specified as part of the standard.
2. Remote terminal is defined with the standard as "all terminals not operating as the bus controller or as a bus monitor." The remote terminal is the electronics necessary to transfer data between the data bus and the subsystem (i.e., the user or originator of the data being transferred). A remote terminal typically consists of a transceiver, an encoder/decoder, a protocol controller, a buffer or memory, and a subsystem interface.
3. Bus controller is responsible for directing the flow of data on the bus. The commands may be for the transfer of data, or the control and management of the bus. The complexity of the electronics associated with the bus controller is a function of the subsystem interface, the amount of error management and processing to be performed, and the architecture of the bus controller. There are three architectures used: word, message, and frame controllers.
4. Bus monitor is a terminal which listens to the exchange of information on the data bus. The standard strictly defines what bus monitors may be used for, stating that the information obtained by a bus monitor be used for off-line applications or to provide a back-up bus controller sufficient information to take over as the bus controller.

The rules under which the transfers occur on the bus is referred to as protocol. The control, data flow, status reporting, and management of the bus is provided by three word types defined by the standard – commands, data, status. Each word type has a unique format yet all three maintain a common structure. The standard defines 10 types of message transmission formats based upon these three words:

1. Command word specifies the function that a remote terminal is to perform. This word is only transmitted by the active bus controller.

2. <u>Data word</u> contains the actual information that is being transferred within a message. Data words can be transmitted by either a remote terminal (transmit command) or a bus controller (receive command).

3. <u>Status word</u> is only transmitted by a remote terminal in response to a valid message. The status word is used to convey to the bus controller whether a message was properly received or the state of the remote terminal (e.g., service request, busy).

Mode codes are defined by the standard to provide the bus controller with data bus management and error handling/recovery capability. For more complete information of this standard see [SP00, Ch. 1; ML1]

12.3.1.2 ARINC 429Digitial Information Transfer System

Early in the process of the Mil Std 1553 development, representatives from the air transport industry realized that the stringent and wide range of military requirements would cause the Mil Std 1553 to be overly complex for the commercial user and would not exhibit the flexibility to accommodate the varying applications of transport aircraft. The net result of subsequent developments led to a new data transfer system exhibiting a high level of efficiency, extremely good reliability, and ease of certification. This became the industry standard data bus referred to as ARINC 429.

Physically, ARINC 429 consists of a single transmitter connected with up to 20 data receivers via a single twisted and shielded pair of wires. It accommodates numeric data encoded in two digital languages, (a) BNR expressed in two's complement fractional notation, and (b) BCD per the numerical subset of ISO Alphabet No. 5. In addition, it is also capable of accommodating discrete items of information either in the unused bits of data words or in dedicated words.

The information output of a system element is transmitted from a designated port to which the receiving ports of other system elements in need of that information are connected. In no case does information flow into a port designated for transmission. A separate data bus is used for each direction when data are required to flow both ways between tow system elements.

The bit-oriented protocol and message exchange procedures for file data transfer between units are designed in a form compatible with the Open Systems Interconnect (OSI) model developed by the International Standards Organization (ISO). The data file and associated protocol control information are encoded into 32-bit words and transmitted over the physical interface.

The physical layer provides the functions necessary to activate, maintain, and release the physical link which will carry the bit stream of the communication. The link layer is responsible for transferring information from one logical network entity to another and for enunciating any errors encountered during transmission. The network layer provides for the decoding of information up to the packet level to determine which node the message should be transferred to. The transport layer controls the transportation of data between a source end-system to a destination end-system. It provides network independent data delivery between these processing end systems.

12.3.1.3 ARINC 629

The Boeing company petitioned AEEC to consider the use of the Digital Autonomous Terminal Access Communications (DATAC) Bus developed to accommodate higher data throughput than

ARINC 429. AEEC accepted Boeing's recommendation for the alternative referred to as ARINC 629.

12.3.1.4 Commercial Standard Digital Bus

The Commercial Standard Digital Bus (CSDB) [GA86] finds its primary implementations in the smaller business and private general aviation aircraft, but has also been used in retrofits of some commercial transport aircraft. CSDB is an asynchronous linear broadcast bus, specifying the use of a twisted, shielded pair cable for device interconnection. The CSDB standard also defines other physical characteristics such as modulation technique, voltage levels, load capacitance, and signal rise and fall times.

The CSDB operates using character-oriented protocol. Data are sent as frames consisting of a synchronization block followed by a number of message blocks. A particular frame is defined from the start of one synchronization block to the start of the next synchronization block. A message block contains an address byte, a status byte, and a variable number of data bytes. The typical byte consists of one start bit, eight data bits, a parity bit, and a stop bit.

Bi-directional transmission can take place between two bus users. If a receiving bus user is required to send data to any other bus user, a separate bus must be used. It is possible to interface CSDB to other data buses. When this is done, a device know as a gateway interfaces to CSDB and the other bus.

CSDB does not fully specify software integration. The standard is very thorough in defining the authorized messages and in constraining their signaling rate and update rate. The determination of which messages are sent within a frame for a particular bus is unspecified. Also, there are no guidelines given for choosing the message sequence or frame loading; this is left to the system designer.

12.3.2 Software Operating System Standards

There are several major real time operating systems that are employed in the development of digital avionics. Two of these operating systems are produced by Wind®River Systems, and by LynuxWorks. These are both governed by standards developed for software mechanization.

Wind®River Systems produces an operating system named VXworks which is currently in version 5 of release. VxWorks is deployed in over 30 million devices. With a focus on performance, scalability, and footprint, VxWorks claims to be able to run device software faster, better, and more reliably. VxWorks meets higher evaluation assurance levels (EAL1-7) and DO-178B safety certification levels (A-E). VxWorks also conforms to ARINC 653 for Integrated Modular Architecture and is the chosen operating system for Smith's Industries FMS.

LynuxWorks produces the LynxOS-178 real time operating system for aviation applications. The core of the LynxOS-178 RTOS package is LynxOS, designed from the ground up as a true, hard real-time UNIX-style OS. LynxOS has been tested and hardened by tens of millions of product deployments since its initial release in 1988. The LynxOS RTOS and the LynxOS-178 RTOS both serve as foundation software for numerous DO-178B certified deployments, including multiple military and aerospace systems certified to DO-178B levels A-E, where A is the most stringent critical safety requirement. The LynxOS-178 operating system is used by Rockwell Collins for the Pro Line 21 avionics suite.

There are several important open standards associated with real time operating systems to which both Wind®River and LynuxWorks adhere. These are The Portable Operating System Interface, POSIX, and the Linux Standard Base, LSB.

The Portable Operating System Interface (POSIX) is an IEEE standardization effort. Although originated to refer to the original IEEE Std 1003.1-1988, the name POSIX more correctly refers to a family of related standards: IEEE Standard 1003.n (where n is a number) and the parts of ISO/IEC 9945. The term POSIX was originally used as a synonym for IEEE Standard 1003.1-1988. A preferred term for that standard, POSIX.1, emerged. This maintained the advantages of readability of the symbol ``POSIX'' without being ambiguous with the POSIX family of standards. POSIX was designed as a standard environment to enable the portability of applications software. This portability of applications software is achieved through the specification of a set of services that every POSIX conforming application can expect to exist on a conforming platform.

The Linux Standard Base, LSB, is an open standard of the Free Standards Group that is attempting to develop and promote standards for the Linux operating system. The set of standards should increase compatibility among Linux distributions and enable software applications to run on any compliant system. In addition, the LSB will help coordinate efforts to recruit software vendors to port and write products for Linux.

The POSIX standard specifies application programming interfaces (APIs) at the source level, and is about source code portability. It is neither a code implementation nor an operating system, but a stable definition of a programming interface that those systems supporting the specification guarantee to provide to the application programmer. The Linux Standard Base is primarily about binary portability and defines a specific binary implementation of an interface to operating system services. In general they build upon the foundations of the POSIX standard.

12.3.3 CDTI Design Standards Example

RTCA SC-186 and SAE G-10 groups provide specific design standards that should be followed by CDTI developers. These standards are divided into the categories of traffic information and display performance requirements and display characteristics.

12.3.3.1 Traffic Information and Display Performance Requirements

RTCA SC-186 has generated a series of source accuracy and display resolution performance requirements for both target information and display parameters for three near-term CDTI applications (see Table 12.7) [RTCA243].

Table 12.7. Near-Term CDTI Application Traffic Information and Display Performance Requirements

	Aid to Visual Acquisition [RTCA243]		Enhanced Visual Approach [RTCA243]		Enhanced Oceanic/Remote Procedures [RTCA243]	
TARGET INFORMATION	Source Accuracy	Display Resolution	Source Accuracy	Display Resolution	Source Accuracy	Display Resolution

Pressure or Relative Altitude (ft)	200	100	100	100	100	100
Relative Bearing (deg)	15	30	3	3	3	3
Relative Range (nmi)	0.5	1.0	0.1	0.25	0.1	1.0
Closure Rate (kt)	-	-	3	1	3	1
Ground Speed (kt)	-	-	2	1	2	1
Ground Track Indication (deg)	-	-	3	3	1	3
Display Parameter						
Max Coasting Time (sec)	15		4		25	
Max Display Update Time (sec)	4		1		4	

12.3.3.2 Display Characteristics

In the recent work by RTCA SC-186 and SAE G-10, a number of recommendations are made about the visual and aural display standards for future CDTIs.

12.3.3.2.1 <u>Visual Display Standards: ([RTMO98] and [S99])</u>

Specific visual display standards include:

<u>Ownship Symbol</u>

- Ownship aircraft symbol color preference is cyan. [RTMO98]

<u>Aircraft Altitude and Altitude Rate</u>

- Aircraft altitude should consist of two digits indicating relative (or absolute) altitude in hundreds of feet, with a "+" or "-" sign associated with it. The color of this data tag shall be the same as the target aircraft symbol. [RTMO98]
- Aircraft altitude display standards should follow TCAS MOPS [T2MO] [S99]
- Aircraft vertical rates in excess of 500 fpm should be noted. [RTMO98] provides no specifics, but [S99] suggests the use of up and down arrows as per TCAS MOPS.

<u>Display Orientation</u>

- Display orientation should be Track-Up or Heading-Up [RTMO98].

<u>Display Prioritization</u>

- Display prioritization of other aircraft targets should be based on: 1) alerts for aircraft with shortest time to closest approach, and 2) range from Ownship. [RTMO98]

Display Prioritization

- Figures and letters should subtend not less than the following vertical angles at the design eye position of the flight crew member who normally uses the instruments:

Primary Data	6 milliradians
Non-essential and secondary data	4 milliradians
Minor descriptive legends	3 milliradians. [S99]

Menu Levels

- In order to avoid disorientation, menu levels should be limited to three (possibly four) and the number of options within a menu level should not exceed ten, and preferably being five to six options. [S99]

Alerts and Resolution Advisories

- Visual alerts and resolution advisories should be located within fifteen degrees of the crew member's centerline of vision (both head up and head down). [S99]

Note: recent efforts by human factors experts have generated new CDTI concepts of symbology and use of color for the display of TIS and ADS-B information [RG99].

12.3.3.2.2 Aural Display Standards [S99]:

Specific aural display standards include:

- Alerting tones should be greater than 8 ± 3 dB above ambient noise with an automatic gain control to maintain this signal-to-noise ratio [S99]

- Frequency of Alerting sounds should be between 500 to 3000 Hz. [S99]

- High urgency signals should be composed of at least two widely spaced frequencies [S99].

- A unique sound should be used for each level of urgency [S99]. Duration of the sound should vary depending on the urgency of the situation.

12.3.3.2.3 Sample Displays

Some sample displays of possible CDTI display concepts include Figure 12.3 and Figure 12.4.

12.4 Certification

Certification of avionics is the critical step to ensuring that the specific component is safe to use. The legal purpose of avionics certification is to document a regulatory judgment that a device meets all applicable regulatory requirements and can be manufactured properly [McCormick, Chapter 23, SP00]. The system level standard for aircraft certification is found in SAE "Certification Considerations for Highly-Integrated or Complex Aircraft Systems" [ARP4754].

Figure 12.3. Candidate RTCA SC-186 CDTI Display [RTMO98]

Figure 12.4. Example CAA Cockpit Display of Traffic Information [CAA98]
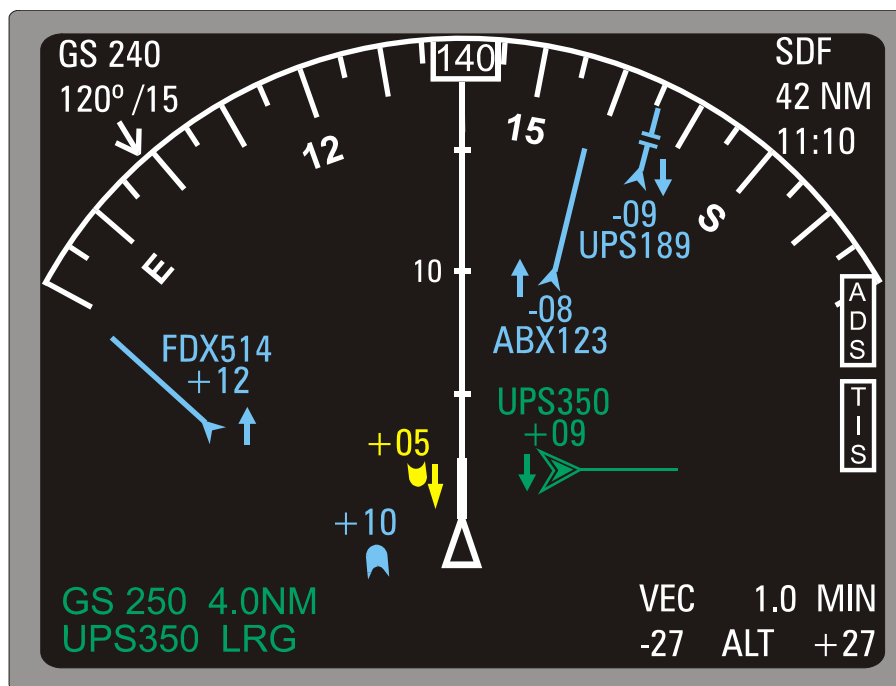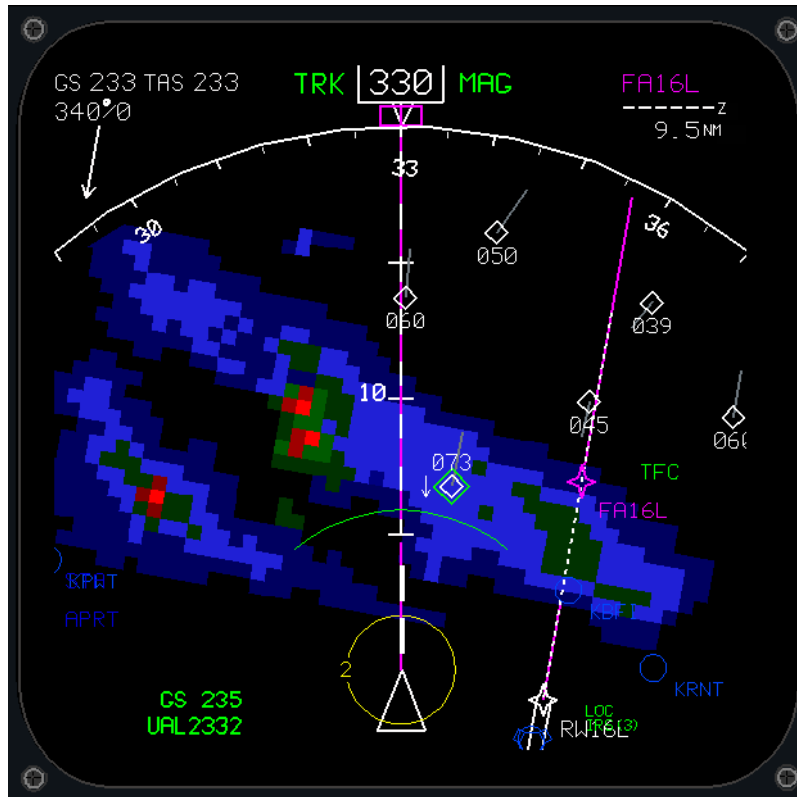
12.4.1 General Certification Process for Avionics

The Code of Federal Regulations (CFR) formalizes federal regulatory activity, such as those that affect civil transports and general aviation airplanes and their operations. The legal requirements for digital avionics systems are derived from CFR Title 14 (Aeronautics and Space), Subtitle A (N/A to Title 14), Volume 1 (Parts 1 – 49), Chapter 1 (Federal Aviation Administration), Subchapter C (Aircraft), Part 23 (Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplane) and Part 25 (Airworthiness Standards: Transport Category Airplanes) Federal Aviation Regulations (FARs)), Subpart F (Equipment).

The Federal Aviation Requirements (FARs) are the legal requirements which applicants must meet to achieve certification. The FARs exist to ensure that <u>minimum</u> safety standards are met. A considerable amount of advisory material supports the FARs to enhance understanding, provide guidance, and to interpret the regulations. These include:

- <u>Orders and Notices</u>: To FAA employees, FAA delegates, and approved organizations regarding <u>how to administer</u> the FARs, clarifications to the FARS, and new policies.
- <u>Advisory System</u>: Advisory Circulars (ACs) provide guidance material to FAA and industry regarding <u>how to meet</u> the FARs.
- <u>Supporting Documentation</u>: Other supporting material recognized by the FAA is used by the FAA and industry to <u>provide the technical basis for showing compliance</u> with the FARs. These data include:
    - Technical Standards Orders (TSOs);
- Society of Automotive Engineers documents, including Aerospace Recommended Practices (ARPs); and
- RTCA documents.

While all the FARs support safety, two regulations tend to be used more than others dealing with avionics, namely:

- FAR 23.1301and FAR 25.1301: Subjective evaluation that a system properly performs its intended functions; and
- FAR 23.1309 and FAR 25.1309: An evaluation of the design to show it performs its functions to an acceptable safety level under any foreseeable operating conditions. Key goals are to assure that:
    - The occurrence of any failure condition which would prevent the continued safe flight and landing of an aircraft is extremely improbable.
    - The occurrence of any failure condition which would reduce the capability of the airplane or the ability of the crew to cope with adverse conditions is improbable.

In order to obtain certification, the avionics system needs to pass through a series of processes initiated by a Letter of Intent to the FAA and followed by the development and submittal of a certification plan to the FAA from the avionics system developer. This certification plan covers the full scope of the intended certification process including:

- Basis for Certification (TC or STC, TSO/PMA/MILSTD/L-M);
- Organizational Responsibilities;
- Means of Compliance;

- Time Schedule;
- Test Plans (incl. location of bench tests, ground tests, flight tests);
- Quality Plan;
- Design and Configuration; and
- Relevant Manuals (incl. Maintenance and Flight) [FFR94].

In addition, representatives of the FAA's Aircraft Certification Service will create S-1 (Means of Compliance) and G-1 (Certification Basis) issue papers.

There are traditionally four separate, but coupled, steps for obtaining equipment certification, including:

- Design approval for equipment, parts, and appliances;
- Installation approval, including Type Certificate (TC) or Supplemental Type Certificate (STC);
- Operational approval of equipment, systems, and procedures to operate the aircraft in air space; and
- Crew approval to operate the aircraft and equipment. [TRL97].

The specifics of the design approval process depend on the specific approval approach taken. Four typical approval approaches include Technical Standards Order, Parts Manufacturing Approval (PMA), military standards (MIL STDs), and List of Materials.

12.4.1.1 Technical Standard Order (TSO)

The highest priority approval approach is TSO approval which provides certification approval for multiple aircraft types. A simplified TSO approval process is shown in Figure 12.5.
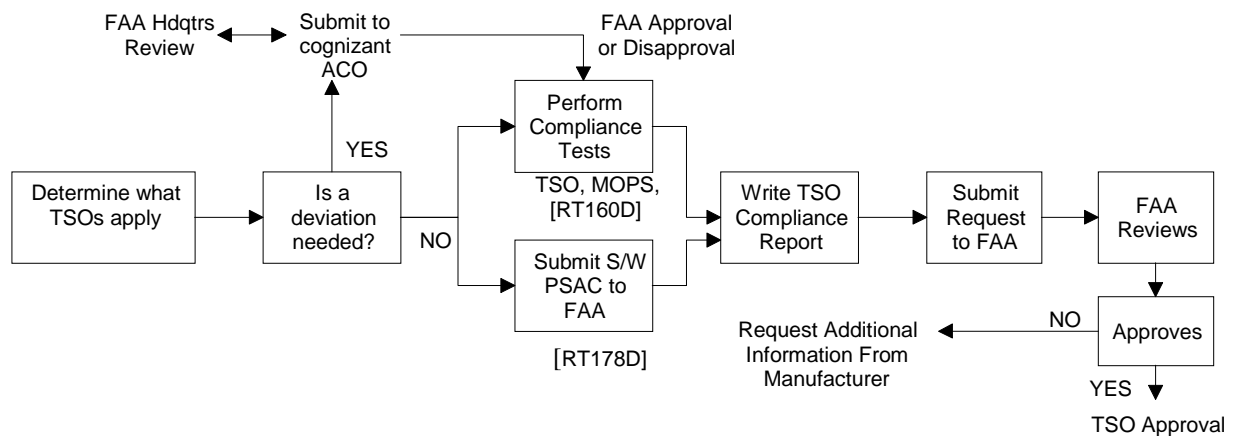
Figure 12.5. Simplified TSO Approval Process from [TRL97]

The TSO is a regulatory instrument that recognizes the broad use of certain classes or products, parts and devices. TSOs contain product specifications, required data submittals, marking requirements, and various instructions and limitations. Many TSOs are associated with avionics: flight-deck instruments, communications radios, ILS receivers, navigation equipment, collision avoidance systems, etc.

TSO-113, Airborne Multipurpose Electronics Displays," is representative of avionics TSOs. Electronic display systems are used for various purposes: display of attitude, airspeed, altitude, navigation, etc. The same physical display device could be used for any or all of these functions, and on many different aircraft types. Recognizing this broad applicability, TSO-C113 is published so that avionics developers can adapt a generic display device to a variety of applications.

Key parts of the TSO approval process includes: hardware performance testing, hardware environmental testing as prescribed in [RT160D], software testing as prescribed in [RT178D], and the conduct of an acceptable safety assessment process, including:

- Functional Hazards Analysis (FHA)
- Preliminary System Safety Assessment (PSSA)
- System Safety Assessment (SSA)
- Common Cause Analysis (CCA) [ARP4761]

Safety assessment is discussed later.

Finally, operational approval is the last process required for certification. This process is run by FAA Flight Standards and Air Traffic Services. The process includes the generation of a Flight Standards Issues and Resolutions Document (IRD), a training and operational approval guidance document, and a letter of authorization for approval by Flight Standards and the generation of required ATC operational approvals by Air Traffic. The documents generated help in providing the needed coordination between FAA Flight Standards, FAA Air Traffic, FAA Aircraft Certification, FAA Headquarters, National Air Traffic Controllers Association (NATCA), the avionics system manufacturers, operators, the maintainers, and inspectors.

12.4.1.2 Supplemental Type Certificate (STC)[AC21]

The STC is granted to organizations other than the aircraft manufacturer, who wish to modify the design of an existing aircraft. Retrofits and upgrades of avionics are common motivations for seeking STC approvals from the FAA. In an STC, the applicant is responsible for all aspects of an aircraft modification. This includes preparation of the certification plan and performance of all analyses specified in the plan.

An applicant for an STC begins the process by completing and submitting FAA Form 8110-12, "Application for Type Certificate, Production Certificate, or Supplemental Type Certificate." This includes the certification basis that is the sum of all applicable FAA regulations and any binding guidance that applies to the aircraft and project.

The certification plan includes:

- A brief description of the modification and how compliance is to be substantiated;
- A summary of the Functional Hazard Assessment;
- A list of proposed compliance documentation;
- A compliance checklist; and
- A project schedule

Extensive analysis and testing are generally required to demonstrate compliance. Results of these analyses and tests must be preserved as part of the STC record. The STC process assumes

modification of at least one prototype aircraft. It is in the aircraft modification that all the engineering analysis (e.g., aircraft performance, electrical loading) comes together. Each components used in an aircraft modification must either be manufactured under an approved production system or examined formally for conformance to its specifications.

An STC holder must demonstrate production capabilities separately. After obtaining an STC approval, the holder may apply for Parts Manufacturer Approval (PMA) authority to produce the parts necessary to support the STC. Alternatively, an STC holder may assign production rights to others, who would then hold PMA authority for the parts in question. PMA approvals are issued by the FAA Manufacturing Inspection District Office.

Installation approval for a Special Type Certificate typically includes the TSO approval, as well as proof of the system's use of PMA approved equipment, and FAA special reviews, ground and flight tests. The special FAA reviews include cockpit resource management and human factors evaluations.

12.4.1.3 Safety Assessment and Environmental Qualification

Avionics developers must consider the aircraft-level hazards associated with any new proposed avionics component. There is an inverse relationship between the severity of a system's hazards and the frequency with which those hazards can be tolerated.

Of the safety assessments, one of the most critical is the Functional Hazard Assessment, or FHA. The FHA is a systematic, comprehensive examination of airplane and system functions to identify potential Minor, Major, Hazardous, and Catastrophic Failure Conditions, which may arise as a result of a malfunction or failure to function. In general, if an FHA concludes that misbehavior of a system has little or no effect on continued safe flight and landing, no further work is needed for the safety assessment. On the other hand, if the FHA confirms that a system can pose nontrivial risk to the aircraft or its occupants, then investigation and analysis must continue. This will include preparation of the Preliminary System Safety Assessment, Fault Tree Analysis, Failure Modes and Effects Analysis, Common Cause Analysis, and a final System Safety Assessment.

In addition to a safety assessment, an analysis of equipment reliability may be required to predict average times between failures of the avionics components. Although this analysis is often performed by safety analysis, the focus is different.

Environmental qualifications are also required of avionics. The standard in this area is RTCA DO 160D, "Environmental Conditions and Test Procedures for Airborne Equipment [RT160D]. This specifies testing for temperature range, humidity, crashworthiness, vibration, susceptibility to radiated and conducted radio frequencies, lightning tolerance and other environmental factors.

12.4.2 Software Certification Considerations

As previously discussed, system software certification standards are covered by RTCA DO178B, "Software Considerations in Airborne Systems and Equipment Certification" [RT178B].

12.4.2.1 General

DO-178B is an assurance standard that is neutral with respect to development methods. The developer can choose their own development methods as long as the areas of planning,

requirements definition, design and coding, integration, verification, configuration management, and quality assurance criteria are satisfied.

DO-178B defines different levels of functional hazard assessment (FHA) classes, depending on the importance of the system to be certified on the safety of flight. These functional hazard classes range from Level A, "Catastrophic", to Level D, "Minor" in decreasing order of flight safety criticality. A chart that depicts the required levels of equipment safety for avionics software per aircraft type is shown in Table 12.8. Examples of Level A software include fly-by-wire primary control systems and full-authority digital engine controllers. At the other extreme, passenger entertainment software is almost all Level E, because its failure has no safety-related effects.

DO178B specifies the information flow between system processes and software processes. The focus of the information flow from the system process to the software process is to keep track of requirements allocated to software, particularly those requirements that contribute to the system safety. The focus of information flow from the software process to the system process is to ensure that changes in the software requirements, including the introduction of derived requirements, do no adversely affect system safety.

Design tradeoffs between software processes and hardware processes are taken into consideration at the system level. Software levels may be lowered by using protective software or hardware mechanisms elsewhere in the system. Such architectural methods include partitioning, use of hardware or software monitors, and architectures with built-in redundancy.

12.4.2.2 Software Life-Cycle

The DO178B life cycle process include the planning process, the software development processes (requirements, design, code, and integration), and the integral processes (verification, configuration management, software quality assurance, and certification liaison). The document defines objectives for each of these processes as well as outlining a set of activities for meeting the objectives.

The planning process defines five types of required data:

- Plan for software aspects of certification
- Software development plan
- Software verification plan
- Software configuration management plan
- Software quality assurance plan

These plans include consideration of methods, languages, standards, and tools to be used during the subsequent development.

DO178b provides only a brief description of the design, coding, and integration processes since these tend to vary substantially between various development methodologies. The one exception to this is in the descriptions to the outputs of each of the processes.

Table 12.8. Figure 2 from 23.1309-1C. Relationship Among Airplane Classes, Probabilities, Severity of Failure Conditions, and Software Development Assurance Levels

Classification of Failure Conditions	No Safety Effect	<----Minor----->	<----Major---->	<--Hazardous--->	< Catastrophic>
Effect on Airplane	No effect on operational capabilities or safety	Slight reduction in functional capabilities or safety margins	Significant reduction in functional capabilities or safety margins	Large reduction in functional capabilities or safety margins	Normally with hull loss
Effect on Occupants	Inconvenience for passengers	Physical discomfort for passengers	Physical distress to passengers, possibly including injuries	Serious or fatal injury to a small number of occupants	Multiple fatalities
Effect on Flight Crew	No effect on flight crew	Slight increase in workload or use of emergency procedures	Physical discomfort or a significant increase in workload	Physical distress or excessive workload impairs ability to perform tasks	Fatalities or incapacitation
Classes of Airplanes:	**Allowable Quantitative Probabilities and Software (SW) Development Assurance Levels (Note 2)**				
Class I (Typically SRE under 6,000#)	No Probability or SW Development Assurance Levels Requirement	$<10^{-3}$ Note 1 P=D	$<10^{-4}$ Notes 1 & 5 P=C, S=D P=D, S=D(Note 6)	$<10^{-5}$ Notes 4 & 5 P=C, S=D P=D, S=D(Note 6)	$<10^{-6}$ Note 3 P=C, S=C
Class II (Typically MRE or STE under 6000#)	No Probability or SW Development Assurance Levels Requirement	$<10^{-3}$ Note 1 P=D	$<10^{-5}$ Notes 1 & 5 P=C, S=D P=D, S=D(Note 6)	$<10^{-6}$ Notes 4 & 5 P=C, S=C P=D, S=D(Note 6)	$<10^{-7}$ Note 3 P=C, S=C
Class III (Typically SRE, STE, MRE, & MTE equal or over 6000#)	No Probability or SW Development Assurance Levels Requirement	$<10^{-3}$ Note 1 P=D	$<10^{-5}$ Notes 1 & 5 P=C, S=D	$<10^{-7}$ Notes 4 & 5 P=C, S=C	$<10^{-8}$ Note 3 P=B, S=C
Class IV (Typically Commuter Category)	No Probability or SW Development Assurance Levels Requirement	$<10^{-3}$ Note 1 P=D	$<10^{-5}$ Notes 1 & 5 P=C, S=D	$<10^{-7}$ Notes 4 & 5 P=B, S=C	$<10^{-9}$ Note 3 P=A, S=B

Note 1: A numerical probability range is provided here as a reference. The applicant is not required to perform a quantitative analysis or substantiate by such an analysis that this numerical criteria has been met for Minor and Major Failure Conditions.

Note 2: The alphabets denote the typical Software (SW) Development Assurance Levels as described in ARP 4754 for Primary System (P) and Secondary System (S). For example, SW Development Assurance Level A on Primary System is noted by P=A.

Note 3: At airplane function level, no single failure will result in a Catastrophic Failure Condition.

Note 4: At airplane function level, no single failure will result in the loss of a function that causes a Hazardous Failure Condition.

Note 5: Secondary System (S) may not be required to meet probability goals. If installed, S must meet stated criteria.

Note 6: A reduction of Software Development Assurance Levels applies only for Navigation, Communication, and Surveillance Systems if an altitude encoding altimeter transponder is installed.

Verification is the technical assessment of the results of both the software development processes and the software verification process. There are specific verification objectives that address the requirements, design, coding, integration, and verification process itself. Emphasis is placed at all stages to assure that there is Traceability from high-level requirements to the final configuration. Verification analyses provide repeatable evidence of correctness and are often algorithmic or procedural in nature. Common types of analyses used include timing, stack, data flow, and control flow analyses. Race conditions and memory leakage are check as part of the timing and stack analysis. Data and control coupling analysis include checks for set/use.

Configuration management (CM) includes:

- Identification of what is to be configured;
- How baselines and Traceability are established;
- How problem reports are dealt with;
- How software is archived and loaded; and
- How the development environment is controlled.

Software quality assurance (SQA) objectives provide oversight of the entire DO-178B process and require independence at all levels. SQA assures that any deviations during the development process from plans and standards are detected, recorded, evaluated, tracked, and resolved. SQA works with the CM process to assure that proper controls are in place and applied to life cycle data.

12.4.3 CDTI Certification Example

The future operational CDTI certification process requires the design and development of the CDTI system according to FAA certification standards and the satisfactory performance in required FAA certification processes. Certification tests are expected for the CDTI system in the area of environmental tests, bench tests, installed equipment tests, and operational tests. Details of the required CDTI system certification standards and processes follow. More information on the FAA design approval process for aircraft data communications systems (being relevant to future CDTI systems) can be found in [AC20]. Recommended installed equipment tests and operational performance tests for CDTI systems can be found in [RTMO98]. More information on the FAA operational approval process for digital communication systems for air carrier aircraft can be found in [AC120].

12.4.3.1 CDTI System Hardware Standards

Applicable standards for the CDTI system hardware from the FARs and supporting documentation, especially, TSOs and ACs include:

- FAR Part 23 and Part 25 Airworthiness Standards
- TSO-C112 ATCRBS/Mode S Airborne Equipment,
- TSO-C113 Multi-Purpose Electronic Displays
- TSO-C129a Airborne Supplemental Navigation Equipment Using the GPS
- FAA AC-23/25.1309-1A Equipment, Systems, and Installations in Part 23/25 Airplanes
- FAA AC-23/25.1311-1 Installation of Electronic Display Instrument Systems in Part 23/25 Airplanes

Technical requirements that cover ADS-B and TIS-driven CDTI systems are in [RTCA242], [RTCA243], [TMO], and [ADMO99].

12.4.3.2 CDTI System Software Standards

For the CDTI, the proper level of certification depends on the particular CDTI application and the level of integration between the CDTI system and more critical systems. In support of "Aid to Visual Acquisition" CDTI applications, the level of certification required can be Level D (which is the case with the current CAA CDTI); however, future use of the system to provide IFR pilot self-separation is expected to increase the functional hazard class level. Also, for standalone CDTI systems, not tightly integrated with other onboard systems, the appropriate level of certification required would be Level D. However, for CDTI displays that are integrated with an onboard navigational display (e.g., in a multi-function display), the level of certification would likely increase to Level C, "Major".

One other important software issue is that the FHA process described earlier may deem some parts of the CDTI system software to have a higher level of criticality than others. For example, in the case of the recent CAA CDTI certification, the Ownship aircraft position information was certified to a level higher than Level D, the FHA level of the majority of the other CDTI software [RTCA131].

A host of certification issues exist with the simultaneous display of data such as traffic, weather, and terrain. Two examples include the different uses of the color red for ground proximity and weather information and the simultaneous display of co-located traffic and small weather cells.

12.4.3.3 CDTI System Standards Interpretation

As with any set of documents that cover a broad array of complex and evolving issues, not all situations are documented in words. Gray areas exist; over time, the applications may change; and many interpretations may not be recorded. The practical adherence to applicable requirements is affected by the specific interpretations of applicable Aircraft Certification Office (ACO) engineers, National Resource Specialist(s) (NRS) who are knowledgeable in the area, and sometimes directorates or the Headquarters Divisions.

In the case of CDTI system certification, there are a number of organizations, offices, and personnel that are most relevant in interpreting the FAA certification standards. The FAA's

Aircraft Certification Service is in charge of the enforcing the safety standards for civil aircraft design and manufacture and is the key service in charge of equipment certification. In addition to the Aircraft Certification Service, the FAA's Flight Standards Service and Air Traffic Service are critical to the operational approval for a new CDTI system.

Applicable National Resource Specialists (NRSs) for CDTI systems include those covering the specialties of (Note: past or present NRS individuals are named in { }):

- Flight Deck Human Factors {Kathy Abbott}
- Aircraft Computer Software {Michael Dewalt}
- Software Quality Assurance {Raghubansh Singh}
- Advanced Avionics/Electrical {James Treacy}
- Electromagnetic Interference {Dave Walen}
- Flight Simulation {Archie Dillard – who is also the head of the SAE G-10 group for Multi-Function Displays}

For CDTI systems that are tightly integrated with the aircraft's flight control system (i.e., the CDTI system includes resolution advisory command guidance), additionally applicable NRSs include:

- Advanced Control Systems {Anthony Lambregts}
- Flight Management {George Lyddane}.

One important issue that has been identified as a particularly subjective topic is the human factors of the human-system interface. Subjective interpretation of the FAR requirements for the system human factors ranges from a requirement that the interface is merely safe for its intended purpose to the requirement that the interface be optimized for its intended purpose.

12.4.3.4 CDTI Certification Trends

The full FAA certification of the first ADS-B and TIS-based CDTI are being driven by the CAA. The CAA CDTI is being certified for the purposes of "Aid to Visual Acquisition" (for more details see Appendix A of [RTCA131].) The CAA CDTI was designed under FAA standards including TSO-C113, Multi-Purpose Electronic Displays, and using guidance from RTCA SC-186 [RTCA242] [RTCA243] [ADMO99]. [RG99]

13. Summary and Conclusions

Multi-modal digital avionics have become the accepted standard in the aviation industry. In investigating the status of avionics design, this investigation of commercial aviation MMDA has focused on the six Key Areas. These are:

1. Description of the multiple functions and integrated modes within the MMDA design for today's commercial and business class aircraft;
2. Sequential or simultaneous operations, functions and modes;
3. Approach used for compliance with certification requirements;
4. Applicable AEEC, ARINC, ICAO, RTCA and other standards;
5. Use of open standards or company proprietary approaches for avionics design; and
6. Summary of hardware and software architectures employed.

In Section 2, as an overview, the sequential and simultaneous elements of the complete avionics suite are described, and this includes their functions and modes of operation. There are several multi-modal avionics examples, but the one that tends to dominate the functioning of the modern transport flight deck is the Flight Management System (FMS); it is described in further detail in Section 3. This is followed in Section 4 by a review of the evolution of the large transport aircraft flight deck going from analog to digital components and then to integrated modes with centralized architectures. Specific advancements that were due to the flight deck designs for the B-737, MD-11, and B-777 are summarized in Sections 5-7. Sections 8 and 9 describe multi-modal digital avionics used today in regional, business, and commuter jets, turboprops, and general aviation. Section 11 described digital avionics components available for the retrofit market. Finally, the state of the art in advanced avionics system architectures, as manifested by the Boeing 7E7, is described in Section 12. Together, Sections 2-12 cover Key Areas 1, 2, 5 and 6 of this effort.

Section 13 summarizes, in turn, the processes and importance of establishing avionics design requirements, the use of accepted guidelines within the design, the role of published standards, and the key elements of the avionics certification process. This covers Key Areas 3 and 4 of this effort.

In the following, we first summarize our findings for Key Areas 1, 2, 5 and 6 in terms of the description of functions, modes, operations and system architectures used in MMDA today. This is followed by a summary of the requirements, guidelines, standards and certification processes resulting from investigating Key Areas 3 and 4. Finally, we conclude what we have found to be the significant gaps in current avionics design in terms of supporting the transformed National Airspace System of the future.

13.1 MMDA Descriptions, Functions, Modes and Architectures

As Key Areas 1, 2, 5 and 6 were investigated, two major themes to the results developed.

Theme 1: Automation and Consolidation.   The transformation to use of digital avionics has highly automated the commercial aircraft flight deck. Multi-modal digital avionics utilization has had two main effects:

1. MMDA has led to development of flight deck functionality and levels of automation that were previously not possible (e.g. FMS, digital flight control, display technology);

2. A common avionics design trend has been to consolidate functions and modes previously performed by separate units into a single package.

In the air transport category and high-end, business aircraft, this evolution has been steadily progressing from the mid 1980s. In contrast, light general aviation has seen a startling revolution as mechanical flight instruments and analog navigation systems have given way to state-of-the-art flat panel EFIS type displays in a matter of the last several years.

Theme 2: Centralized Architecture.   Digital avionics architecture has evolved away from distributed digital systems that mirrored the architecture of old analog systems (only with digital components) and towards a centralized architecture. The centralized architecture is more analogous to a modern computer running multiple processes governed by one operating system. It runs with a single operating system saving the space and added complexity of having to duplicate hardware and operating systems for all the different applications. This trend has manifested itself on the B-777 and numerous business jet architectures.

The following summarizes our findings regarding flight deck automation, consolidation of functions and the evolution to centralized architectures.

13.1.1 Cockpit Automation

One major example of cockpit automation is the utilization of the Flight Management System. The FMS can fly the aircraft (through the use of the auto-flight system) from initial climb all the way to the final approach course. The FMS comprises two units, the Flight Management Computer (FMC) and the Control Display Unit (CDU or MCDU 'Multi-Function CDU'). A basic schematic of a typical FMS installation is shown in Figure 13.1**Error! Reference source not found.**. From the drawing, it can be seen that the FMC interfaces with most other avionics systems on the aircraft. These systems include the Flight Control Computers (FCC), auto-throttle (A/T), all navigation radios, all data link systems, and other I/O peripherals, such as displays and the fuel quantity indicators.

Cockpit automation has eliminated the need for a flight engineer on large transport aircraft using systems such as the EICAS (Engine Indication Crew Alerting System). This significant reduction in direct operating cost was made possible by advances in system control technology that enabled automatic execution of proven flight deck procedures without excessive redesign of the system or procedures [SP00].

As part of the automation processes, the aircraft systems are monitored for proper operation by the Automatic Systems Controllers (ASC). In most cases, system reconfiguration as a result of a malfunction is automatic, with manual input being required for irreversible actions, such as engine shutdown, fuel dumping, fire agent discharge, or generator disconnect. A 'dark cockpit' philosophy is adopted in that during normal operations all annunciators on the overhead panel are extinguished; a dark cockpit confirms to the crew that all systems are operating normally and are properly configured.

13.1.2 System Consolidation

Examples of system consolidation include the elimination of numerous analog dials with a single flat panel display, the consolidation of all navigation and communication radio functionality into single units, and the consolidation of attitude, air data, and inertial reference systems all into a single box. This evolution is moving away from the distributed architecture that was used on the MD-11, with all boxes separate and connected with ARINC429 data buses. Now Integrated

Modular Avionics (IMA) is becoming the mainstream concept. In these systems, the FMS, EFIS, displays, etc. are no longer separate boxes, but rather software on a centralized system. The end result is a compounding of features consolidation resulting in several major systems running on one hardware element.

Systems that used to exist as separate units are now often combined into the same unit. This is often done with voice and navigation radios, and aircraft sensors. For example, the Honeywell Primus integrated avionics system has replaced the Air Data Computer (ADC), Global Position System (GPS) sensor, and Inertial Reference System (IRS) or Attitude/Heading Reference System (AHRS) with the Integrated Sensor Suite (ISS), a complete primary sensor system. Each ISS function consists of three sensor components which include the small line-replaceable Inertial Measurement Unit (IMU), Air Data Module (ADM), and GPS Sensor Module. Raw information from the sensors is processed by the system to provide all the inertial, positional and air data information used by all other functions within the avionics system [H98].

Similarly, the Primus Epic digital remote-mounted radio system (see Figure 13.2) encompasses the standard navigation and communications functions, including VOR, ADF, DME, ILS, VHF Communication and Mode S Transponder modules. The radio system uses line replaceable units (LRUs) from the Honeywell Primus II integrated radio system, housed in dual remote mounted radio cabinets [H98]. The result is that fewer individual units are needed and less wiring is required. In addition to the classic navigation features, the Primus system offers Built-In Test Equipment (BITE) and integrated maintenance features.
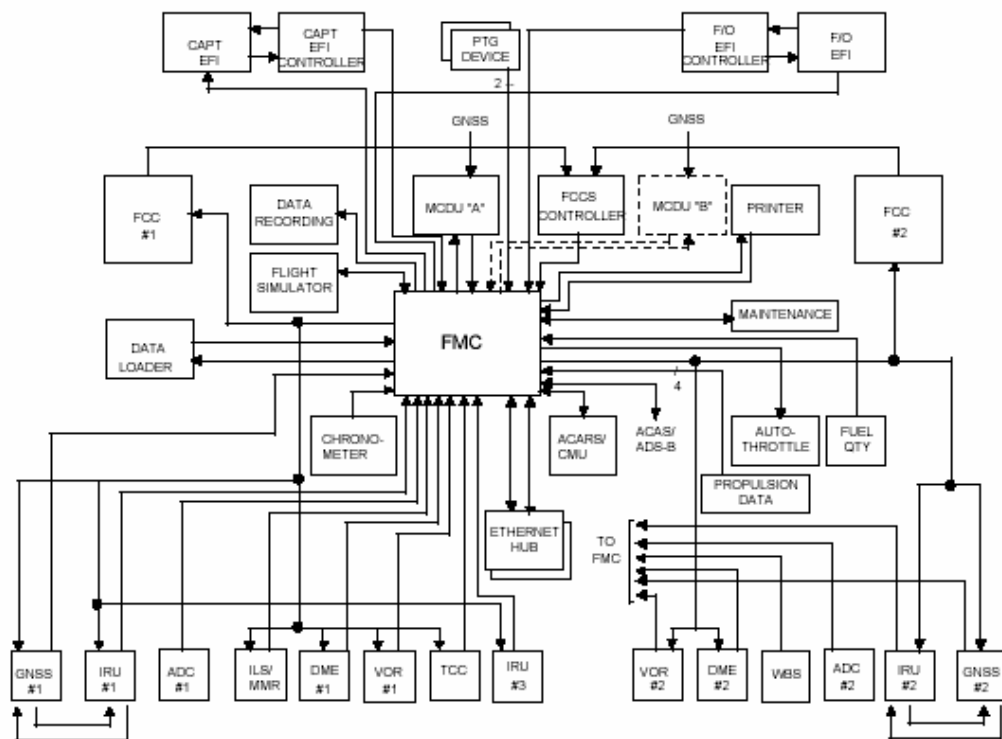
Figure 13.1. Example implementation of FMS architecture as presented in ARINC 702A-1[ARI00]
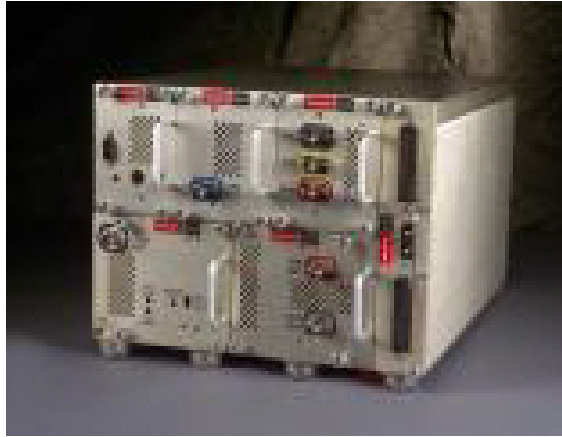
Figure 13.2. Photograph of the Primus Integrated Radio System

Rockwell Collins offers integrated radio systems as well. An example of such a system is the NAV-4000 shown in Figure 13.3. The NAV-4000 includes both the VIR (VOR/ILS/MKR) and ADF functionality in a single LRU.

Figure 13.3. Photograph of the NAV-4000

Feature consolidation has also reached a high level in general aviation as companies like Garmin build single purpose units to encompass all navigation and communication requirements. An example of such a multi-modal instrument is the Garmin GNS-530, shown in Figure 13.4. The GNS-530 provides WAAS-upgradeable IFR GPS, Com, VOR, LOC and glide-slope functions with color moving map all rolled into one. An associated Jeppesen database contains all airports, VORs, NDBs, Intersections, FSS, Approach, DPs/STARs and SUA information.

However, this trend toward hardware consolidation has complicated the associated avionics software. New operating systems now focus on partitioning applications running on a single system. Software is designed to run on multiple platforms. With software already consuming 70-80% of the development cost of new avionics and with software being the highest risk item in avionics development, some manufacturers wonder if the new focus on minimizing hardware at the cost of additional software is wise. This argument is further supported as the cost of new

hardware diminishes and the capabilities rise. In today's computing market, the hardware / software cost ratio is approaching a small fraction.

Figure 13.4. Garmin GNS – 530

### 13.1.3 Digital Avionics Architecture Evolutionary Path

Since the 1970s, the general architecture of air transport flight decks has progressed through five major phases of development. These are:

1. Electromechanical (non-FMS);
2. Electromechanical with FMS;
3. Hybrid / EFIS with FMS;
4. Fully digital, distributed, glass cockpit; and
5. Centralized computing architecture.

The electromechanical flight deck of the early 1970s (see Figure 13.5) consisted of electromechanical air data instruments such as airspeed, Mach, and altimeters and mechanical attitude gyros. The flight deck was automated with an analog autopilot and auto-throttle. The navigation instruments consisted of VOR/DME/ADF that needed to be manually tuned.

The inclusion of the FMS in the electromechanical flight deck (see Figure 13.6) connected various systems that previously were completely independent from one another. The FMS provided guidance commands to the auto flight system rather than having the auto flight system drive directly from the navigation instruments. The FMS also auto-tuned the navigation radios and made use of the inertial navigation system to accurately determine position. The FMS accessed the engine and fuel system data to estimate and optimize aircraft performance such as range and endurance. The rest of the cockpit remained unchanged.

In the mid 1980s, as computer systems became more powerful, some of the original cockpit displays were replaced with electronic equivalents resulting in a hybrid flight deck that had digital avionics mixed in with the older analog systems. (See Figure 13.7) These electronics instruments consisted of the Electronic HSI, which gave a graphical image of the route the FMS was using along with much other information that previously could not be viewed graphically.
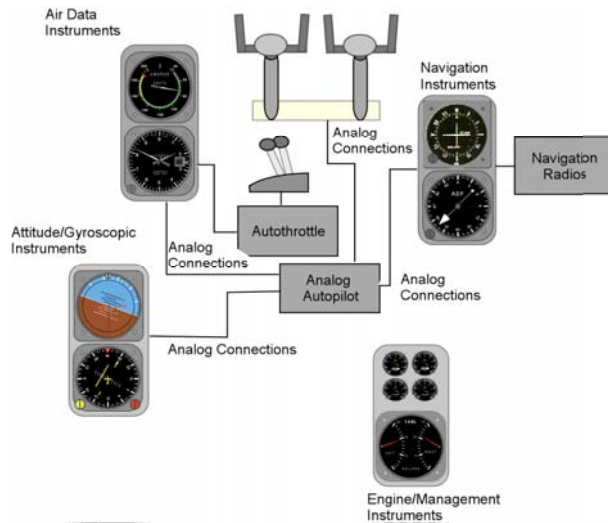
Figure 13.5. Schematic of Pre-FMS electromechanical flight deck
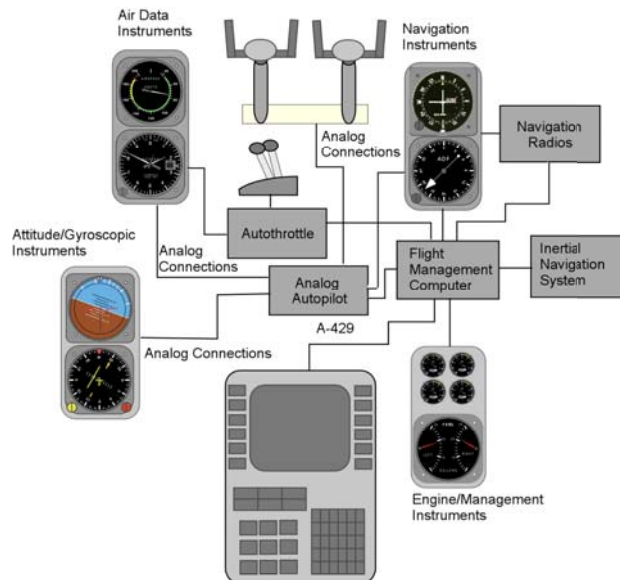
Figure 13.6. Electromechanical Flight deck with an FMS

The system provided a much better representation of the route data than what had been provided previously and gave the pilot much better situational awareness. However, the electromechanical pitot-static instruments, such as airspeed, Mach, and altitude, were retained.

The next evolutionary step was moving to the full digital, distributed, glass display flight deck. All analog instruments and systems were removed. The electronic attitude display was upgraded to include all air data (pitot-static) information in addition to attitude display and is referred to as the primary flight display (PFD). Additionally, the EICAS (Engine Instrument and Crew Alerting System) was added. The EICAS monitors system sensors and provides a high level synopsis of aircraft systems. In this system, all aircraft state information comes from the ADIRU (Air Data Inertial Reference Unit). The data exchange unit transfers information and provides the graphics for the displays. Digital autopilots and auto-throttles operate the aircraft while the FMS

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is still the center of flight operations. All data links are digital. Many distributed digital entities are sharing information through digital data link [SP00]. This is depicted in Figure 13.8.
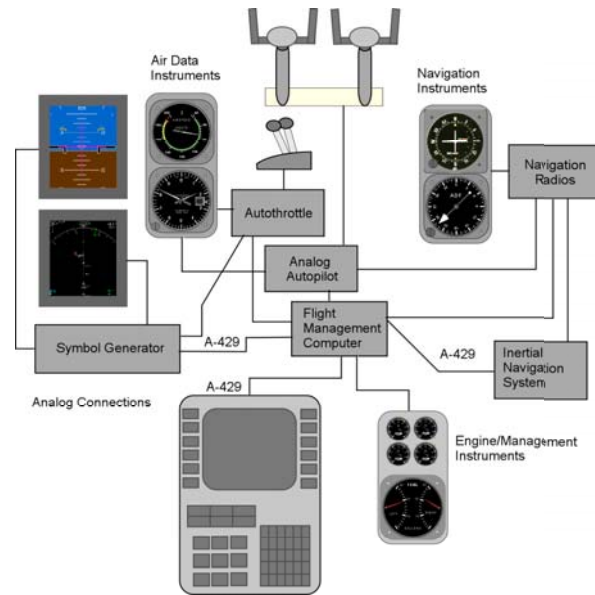
Figure 13.7. Hybrid EFIS flight deck circa 1988
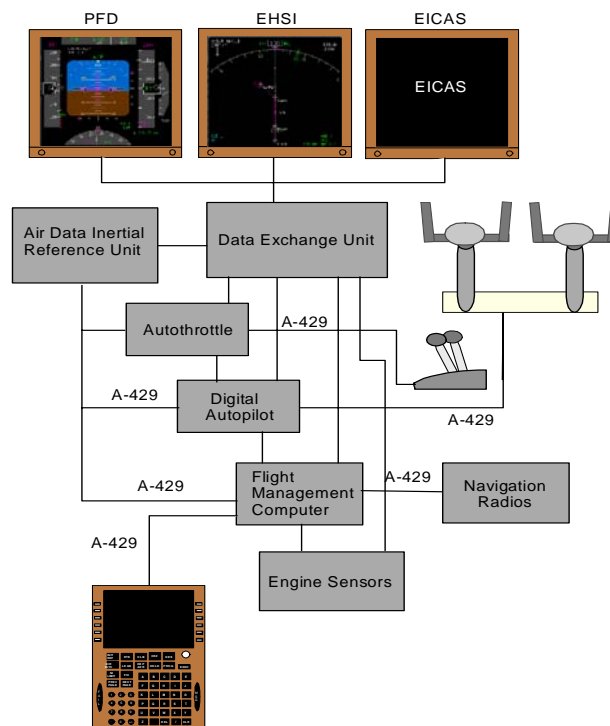
Figure 13.8. Fully Digital / Next Generation Flight Deck

The fifth phase of development, which currently represents the state-of-the-art in flight deck design, is the Centralized Computing Architecture. Avionics manufacturers have realized that weight and complexity could be reduced if all software processes could run on a centralized computing platform. This platform could conceivably host the major flight systems, such as FMS, auto-flight systems and the EICAS system, all on one platform. The advantage to this architecture is that all systems could share the same operating system, I/O features, and memory. Figure 13.9 represents a greatly simplified representation of such a system to emphasize the centralized nature of current design. From the pilot's perspective, there is little functionality change between the old and the distributed digital system [SP00].
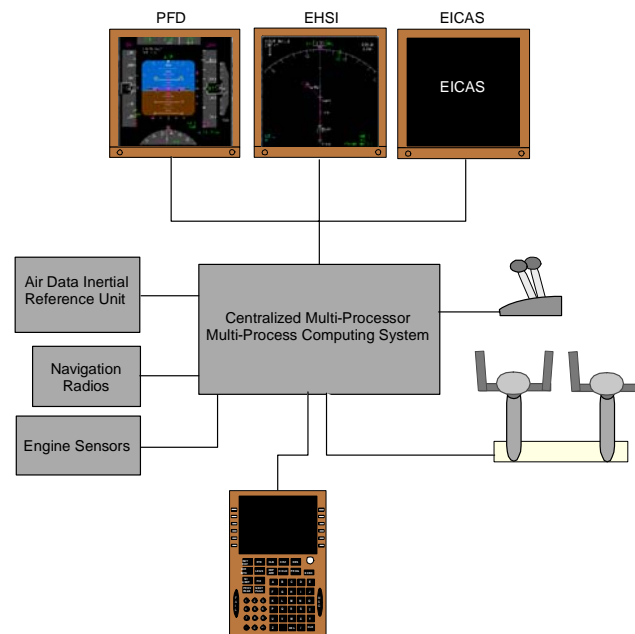
Figure 13.9. Centralized Computing Architecture

The centralized architectures are often referred to as Integrated Modular Avionics (IMA). While there are various designs for IMA, they all share a basic theme of a number of avionics cabinets that are connected together. These include other peripheral equipment by means of a number of multiple-access serial data buses as shown in Figure 13.10. Each cabinet is seen as a high power computing module which replaces many, single-purpose Line Replaceable Units (LRU) [SP00]. Each cabinet contains a selected mix of Line Replaceable Modules (LRM) including core processors, power supplies, and I/O devices, along with other special functions.

The modular cabinet in an IMA system supports one or more avionics applications and allows independent execution of those applications. This can be correctly achieved if the system provides partitioning, i.e., a functional separation of the avionics applications, usually for fault containment (to prevent any partitioned function from causing a failure in another partitioned function) and ease of verification, validation and certification.

The Boeing 777 Airplane Information Management System (AIMS) implements the IMA concept in an architecture that supports a high degree of functional integration and reduces duplicated resources. The conventional LRUs of the MD-11 vintage aircraft are replaced with

dual integrated cabinets which provide the processing power and input/output (I/O) hardware and software required for the following functions:

- Flight Management (FMS);
- Displays;
- Central Maintenance;
- Airplane Condition Monitoring;
- Communication Management and Flight Deck Communication; and
- Data Conversion (ARINC 429 / 629 data bus conversion).
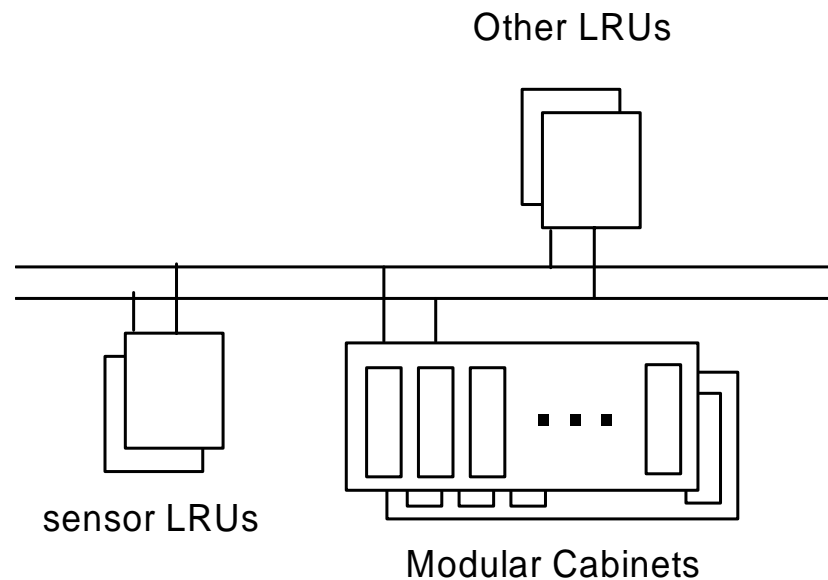
Figure 13.10. Simplified representation of Integrated Modular Avionics (IMA) architecture [SP00]

The integrated cabinets are connected to the airplane interfaces via a combination of ARINC 429, ARINC 629 and discrete I/O channels. Figure 13.11 provides a detail of the processes contained in the AIMS cabinet. [U02]

13.1.4 The Case Against Centralized Architectures

While the industry trend has been to move away from distributed architectures towards centralized multi-processor, multi-process avionics, there are number of reasons to suggest that this trend may not result in future optimal architectures in the face of rapidly changing computing technologies. The large commercial markets for computing technologies have continued to reduce the cost of computing resources and have provided smaller, cheaper and more reliable hardware with considerably higher performance. For instance, an FMC of the early 1990's that required a large 10" wide box can now be implemented on a single card [SP00]. Similar advances have occurred with sensors displays and data buses.

At the same time, the complexity of the systems on board aircraft has increased. Aircraft carry technologies such as full digital auto-flight systems, fly-by-wire flight controls, FMS, and highly automated systems management software. Most of the development of these products is in

software rather than hardware. Today, software consumes 70-80% of the development budget for new avionics, and its development is by far the highest cost and causes the greatest schedule risk.
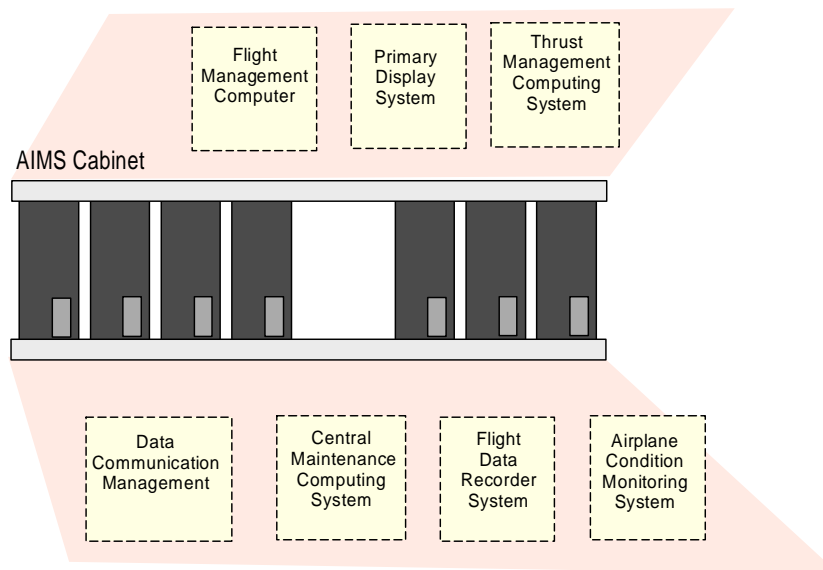
Figure 13.11. B777 Systems supported by the AIMS Cabinet

Therefore it becomes harder to justify developing large centralized computing structures to minimize the cost of hardware development, considering that additional software in the form of specialized operating system and partitioning software must be developed to accommodate the centralized architecture. In short, the centralized architecture tends to minimize the cost (size, weight, power usage in addition to acquisition cost) of hardware at the expense of more software when the natural market trend is already to minimize the cost of hardware.

Because the centralized architectures may require software to be hosted on different platforms, much effort has to be made to insure that the application software is independent of the hardware, adding additional cost to software development and testing. Additionally, the re-hosting of existing software on new hardware with new operating systems bears an additional cost in terms of software development and reuse [SP00].

Two advances have given renewed interest to distributed architectures. These are:

1. The advent of "Smart" peripherals. The reduction in the size of electronics has enabled boxes that used to be stored in a centralized location to be moved to various locations in the aircraft. Examples of smart peripheral devices along with their location include:

   - Full Authority Digital Engine Control (FADEC) - on the engine;
   - Air Data Module (ADM) - fuselage skin;
   - Cabin entertainments systems - cabin; and
   - Auto-throttle actuators - under flight deck floor.

   It is possible to provide considerable functionality within the peripheral devices without increasing their size using modern micro-circuits. It is likely that the trend will continue and smart peripherals will occupy displays, flight control actuators, landing gear sensors, fuel quantity indicators, and radios and navigation sensors [SP00].

2. High speed serial buses. High-speed serial buses are starting to appear that are based on commercial (non-aviation) standards. The industry has started work on Ethernet and the first example of FDX (Full Duplex Ethernet). Airbus is planning to use a variant of FDX (AFDX) as the main avionics and system buses on the A-380. Likewise, Boeing is considering the use of AFDX on the B-7E7 [SP00]. The high speed buses make accessing peripherals easier since they can now be plugged into a local area network based on multiple hubs, rather than using the antiquated ARINC 429. ARINC 429, besides being at best 100 times slower than a standard 100 Mbps Ethernet, can only carry data from one source and so each item needs as many inputs as the number of buses that it expects to receive data from.

13.1.5 Open and Proprietary Design Approaches

Avionics manufacturers have traditionally used proprietary design methods and characteristics as these gave the manufacturers their competitive edge, and specific avionics component interface requirements locked in use of complementary products from the same manufacturer. However, there is a move toward use of open standards in software design as different manufacturers design avionics components of large, complex systems for a particular airframe that must be compatible.

There are several major real time operating systems that are employed in the development of digital avionics. Two of these operating systems are produced by Wind®River Systems, and by LynuxWorks. Wind®River Systems produces an operating system named VXworks which is currently in version 5 of release. VxWorks meets higher evaluation assurance levels (EAL1-7) and DO-178B safety certification levels (A-E). VxWorks also conforms to ARINC 653 for Integrated Modular Architecture and is the chosen operating system for Smith's Industries FMS.

LynuxWorks produces the LynxOS-178 real time operating system for aviation applications. The core of the LynxOS-178 RTOS package is LynxOS, designed from the ground up as a true, hard real-time UNIX-style OS. The LynxOS RTOS and the LynxOS-178 RTOS both serve as foundation software for numerous DO-178B certified deployments, including multiple military and aerospace systems certified to DO-178B levels A-E. The LynxOS-178 operating system is used by Rockwell Collins for the Pro Line 21 avionics suite.

There are several important open standards associated with real time operating systems to which both Wind®River and LynuxWorks adhere. These are The Portable Operating System Interface (POSIX), and the Linux Standard Base (LSB).

Although originated to refer to the original IEEE Standard 1003.1-1988, the name POSIX more correctly refers to a family of related standards: IEEE Standard 1003.n (where n is a number) and the parts of ISO/IEC 9945. POSIX was designed as a standard environment to enable the portability of applications software. This portability of applications software is achieved through the specification of a set of services that every POSIX conforming application can expect to exist on a conforming platform. The POSIX standard specifies application programming interfaces (APIs) at the source level, and is about source code portability. It is neither a code implementation nor an operating system, but a stable definition of a programming interface that those systems supporting the specification guarantee to provide to the application programmer.

The Linux Standard Base is an open standard of the Free Standards Group that is attempting to develop and promote standards for the Linux operating system. The set of standards should

increase compatibility among Linux distributions and enable software applications to run on any compliant system. The LSB is primarily about binary portability and defines a specific binary implementation of an interface to operating system services. In general, LSB builds upon the foundations of the POSIX standard.

13.2 Avionics Design Requirements, Guidelines, Standards and Certification Practices

13.2.1 Design Requirements

The first step in the avionics design process is to define the customer requirements for the new product. Inherently, the avionics designer must ask and answer: What is the reason for developing this new design? Is it an entirely new product based upon an entirely new concept or innovation, or does it address problems with or improve upon an older product because of one or more reasons? Proper requirements are the foundation for well-designed avionics. Whatever the sources of requirements, and whatever the methods used for their capture and refinement, an avionics designer must be able to demonstrate that a new system's requirements – performance, safety, maintenance, continued airworthiness, etc. – have been addressed comprehensively.

In Section 12.1 several examples are used to illustrate the purposes that drive the design requirements as the essential first step in creating a new avionics function or system. These include enhancing safety, extending the aircraft mission, or improving the product life cycle cost.

13.2.2 Design Guidelines

Another important aspect of avionics design is attention paid to the design guidelines, or philosophies, that have been established over years of development by a particular manufacturer or that of a particular customer, especially related to human interface with the automation functions that avionics systems provide to the flight deck. In Section 12.2, the contrast between the Airbus philosophy of using hard limits of envelope protection vs. the soft limits of the Boeing philosophy where the pilot has greater authority are presented.

Another general example of customer-based design guidelines might be that all flight decks, regardless of aircraft type, look alike with the same control feel and responsiveness. This would enable the flight crew to train for a particular aircraft type but be able to quickly adapt to another type. It would also reduce training time and cost.

Reference RTCA/DO-254 [RTCA254] provides design assurance guidelines for developing airborne electronic hardware. This is a very important design guidance document for digital avionics, and it consists of a detailed summary of best practices by the engineering organizations from international aviation manufacturers. Its intention is to provide this guidance for the development of airborne electronic hardware such that it safely performs its intended function in its specified environments.

RTCA/DO-178B [RT178B] presents the guidelines for software development that are generally referred to for certification of new avionics. These guidelines are specifically oriented to ensure levels of software performance consistent with achieving flight safety at an agreed upon level. DO-178B defines five particular failure conditions and the software level of certification (A-E) that must be achieved to attenuate and reduce to very low probabilities that such failure

conditions would occur. The software level of certification implies the level of effort required to show compliance with certification requirements for the failure condition category.

13.2.3 Standards

There are several important standards that come into play in design of digital avionics. These have been established by the airlines and the FAA so that avionics manufacturers can build products that are consistent in performance and so that one manufacturer's avionics components can be readily intermingled with the avionics components of other manufacturers. For example, the Collins radio or the Honeywell GPS receiver works with the Smiths FMS. In Section 12.3, these standards are described, and they are found in AEEC, ARINC, ICAO, and RTCA documents, several which are referenced throughout this report. As examples of avionics standards, the digital data bus and the cockpit display of traffic information (CDTI) are used to illustrate the content of such documents.

As digital avionics becomes the prevailing standard, much of the expected functionality of these new systems continues to be documented by technical committees formed of avionics manufacturers and other aviation stakeholders. Display symbology, autopilot features, digital radios, navigation equipment, and FMS capabilities, for example, are now well documented in ARINC specifications. As new systems come on line, such as the Terrain Awareness and Warning System (TAWS), the general design aspects of these systems are standardized as well.

13.2.4 Certification Processes

Section 12.4 outlines the certification processes. Certification of avionics is the critical step to ensuring that the specific component is safe to use. The legal purpose of avionics certification is to document a regulatory judgment that a device meets all applicable regulatory requirements and can be manufactured properly [McCormick, Chapter 23, SP00]. The system level standard for aircraft certification is found in SAE "Certification Considerations for Highly-Integrated or Complex Aircraft Systems" [ARP4754].

The Federal Aviation Requirements (FARs) are the legal requirements which avionics designers must meet to achieve certification. The FARs exist to ensure that <u>minimum</u> safety standards are met. A considerable amount of advisory material supports the FARs to enhance understanding, provide guidance, and to interpret the regulations. These include:

- <u>Orders and Notices</u>: To FAA employees, FAA delegates, and approved organizations regarding <u>how to administer</u> the FARs, clarifications to the FARS, and new policies.
- <u>Advisory System</u>: Advisory Circulars (ACs) provide guidance material to FAA and industry regarding <u>how to meet</u> the FARs.
- <u>Supporting Documentation</u>: Other supporting material recognized by the FAA is used by the FAA and industry to <u>provide the technical basis for showing compliance</u> with the FARs. These data include:
  - Technical Standards Orders (TSOs);
- Society of Automotive Engineers documents, including Aerospace Recommended Practices (ARPs); and
- RTCA documents.

While all the FARs support safety, two regulations tend to be used more than others dealing with avionics, namely:

- FAR 23.1301and FAR 25.1301: Subjective evaluation that a system properly performs its intended functions; and
- FAR 23.1309 and FAR 25.1309: An evaluation of the design to show it performs its functions to an acceptable safety level under any foreseeable operating conditions.

In order to obtain certification, the avionics system needs to pass through a series of processes initiated by a Letter of Intent to the FAA and followed by the development and submittal of a certification plan to the FAA from the avionics system developer.

13.3 Gaps in Avionics Development

It is unlikely that there are significant gaps in the design of software or architecture for avionics manufacture. The next big innovations in avionics systems work will most likely involve implementing new ideas to integrate air traffic management (ATM)-flight deck functions in more dense airspace and to enable smaller aircraft to be flown safely with only a single pilot. Some of these current gaps that require new avionics innovations are now discussed.

13.3.1 Auto-throttle

An auto-throttle has been a basic element on transport aircraft for a long time, so it is amazing how many aircraft still do not have one. While most airliners have auto-throttles, most business aircraft do not. In the current NAS, aircraft can get away without having an auto-throttle; however, in the future, new interactions between ATM and aircraft may necessitate the use of an auto-throttle for both flight efficiency and increased airspace capacity. For instance, without the auto-throttle, aircraft cannot fully utilize their FMS and are unable to accurately meet Required Times of Arrival (RTA) or 4D fixes. These aircraft will not be able to fly precise trajectories required for trajectory negotiation and other future ATM concepts. There currently is no auto-throttle for any light piston aircraft.

13.3.2 ATM Negotiation

Current flight deck avionics have not developed to the stage where the FMS can be used to negotiate flight plan changes and 4D trajectories by interacting with ATM automation. This capability will be necessary as the ATM system becomes more automated and more aircraft have to be flown within increasing dense, complex airspace.

13.3.3 True 4D Flight Trajectories

As discussed, the FMS can drive the aircraft to meet a time of arrival (the RTA) at a future waypoint. However, for true 4D trajectory control, the FMS and flight control system must be able to compute and guide to a series of RTAs at sequential waypoints. This process must take into account the performance envelope of the aircraft and the need to use the multiple RTA for negotiating efficient flight trajectories in the form of amended flight plans.

13.3.4 Self Separation Capability

To enable more efficient and dense air traffic, the flight crew must participate in increasing responsibilities for separation assurances. This includes the capabilities to self separate, provide station keeping with respect to other aircraft, and to merge and self space into streams or strings of aircraft going to common airports or travel lanes. This requires greater use of the CDTI, ADS-B, FMS, and trajectory negotiation between adjacent aircraft and sequential aircraft negotiating with air traffic management automation.

13.3.5 Single Pilot Operations

With the advent of the Micro-jet and the potential use of such aircraft in FAR Part 135 air-taxi operations, there have been new issues raised with respect to aircraft being flown with only a single pilot. For small jet aircraft air-taxi to be economically viable, many operators want to operate with only a single pilot. While this type of operation has generally been accepted by insurance companies and the FAA when done in light piston/turboprop aircraft, generally the operation of a jet aircraft is thought to require a two-pilot crew.

The Eclipse, Mustang and other micro-jets will most definitely be certified under FAR Part 23 for single pilot operation; however, there are still problems when using jets for *hire* in single pilot operations. Legally, the Federal Air Regulations Part 135 do not explicitly prohibit single pilot operations, but local Flight Standards District Offices (FSDOs), who ultimately have the regulatory authority to approve Part 135 operations, generally do not approve single pilot jet operations. More generally, the aviation community opinion is that no Part 135 operator with integrity operates jet aircraft with a single pilot. Insurance may be difficult or impossible to obtain for single pilot commercial transport operation. Insurance companies have monitored single-pilot turbine operations for years. Insurance companies are increasingly saying "no" to some single-pilot operations when, in their estimation, there is simply too much on the line to risk offering the coverage. With the right technology development, this cultural attitude can change, but it is likely to take time.

Innovative technologies that can solve this problem are imaginable, and they will most likely focus on building automated 'first-officer' capability into the flight deck. This capability would take the current flight deck past the point of merely a highly automated system, and start encompassing some form of artificial situational awareness. This situational awareness may require the aircraft to have some means to monitor the condition of the pilot as well as its own systems. In extreme cases of pilot incapacitation, the aircraft may have to assume control and execute some form of emergency auto-land capability.

In summary, multi-modal digital avionics has many components, represents complex engineering and manufacturing, and has a rich history of development. There are still MMDA research and development tasks that are required to make commercial transport and general aviation aircraft safer, easier to fly, less expensive to purchase and use, easier to maintain, and more comfortable to the flying public. The economic pressures of providing greater commercial air transport system capacity and customer mobility also support this continuing avionics evolution.

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