



VILNIUS GEDIMINAS TECHNICAL UNIVERSITY
ANTANAS GUSTAITIS AVIATION INSTITUTE
DEPARTMENT OF AVIONICS

Cagdas Efe BALIN

**INVESTIGATION OF AIRCRAFT TECHNICAL DIAGNOSTICS
SYSTEMS**

Master's degree Thesis

Aviation Electronics Study Programme, State Code 62401T208
Avionics Specialization
Electronics Engineering research field

Vilnius, 2010

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CONFIRMS

Department Head

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Annotation

This work is intended to investigate the Aircraft Technical Diagnostics Systems by focusing on *Central Maintenance Systems* and the *Fault Detection and Isolation* (FDI) process among the avionic components. A review about the *Computer Control Systems* and background about the *Avionic Architecture* is presented prior to introducing to most popular FDI method; *model-based diagnosis*. The discussions about the onboard FDI practices are followed by a maintenance hangar FDI perspective which was concluded as a result of the field research. The outcomes of the field research and pointing the “real” fault isolation are analyzed to point the practical needs of a hangar FDI tools. Subsequently, a proposal technique, which can improve fault isolation by preventing *No-Fault-Found* (NFF), is given by discussing the methods to implement it. Finally, the results of investigation and conclusions of analysis are presented.

Structure: introduction, analytical review, investigation and analysis, conclusions and references.

Thesis consist of: 72 p. text without appendixes, 33 pictures, 3 tables, 30 bibliographical entries.

Appendixes included.

Keywords: Aircraft Maintenance, Fault Detection & Isolation, Model-Based Diagnosis, Central Maintenance System, No-Fault-Found.

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Abbreviations

BITE	Built-in Test Equipment
FID	Fault Detection and Isolation
CMS	Central Maintenance System
DR	Dispatch Reliability
DMC	Direct Maintenance Cost
NFF	No-Fault-Found
PFCS	Primary Flight Control System
ADIRS	Air Data and Inertial Reference System
AIMS	Airplane Information Management System
FMS	Flight Management System
SFCS	Secondary Flight Control System
ACE	Actuator Control Electronics
FCPC	Flight Control Primary Computer
FCSC	Flight Control Secondary Computer
AFDS	Automatic Flight Director System
CDU	Control Display Unit
PFCC	Primary Flight Control Computer
SFCC	Secondary Flight Control Computer
IRS	Inertial Reference System
FMC	Flight Management Computer
CMC	Central Maintenance Computer
LRU	Line Replaceable Unit
MAT	Maintenance Access Terminal
IMA	Integrated Modular Avionics
ARINC	Aeronautical Radio, Incorporated
MRB	Maintenance Review Board
MPD	Maintenance Planning Document
FIM	Fault Isolation Manual
APU	Auxiliary Power Unit
FDR	Flight Data Recorder
SB	Service Bulletin
AMM	Aircraft Maintenance Manual
AHM	Aircraft Health Management
MTBF	Mean-time-between-failures
MTBCF	Mean-time-between-critical-failures
MTBUR	Mean-time-between-unit-replacement

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Appendix A. The Article presented for the Editorial Board of journal “Science – Future of Lithuania” 2010, vol.2.

Appendix B. The Article presented for the Editorial Board of journal “Science – Future of Lithuania” 2009, vol.2.

Appendix C. Certification of award for presentation in “Aviation Technologies Conference 2010” held in Antanas Gustaitis Aviation Institute on 15 April 2010.

INTRODUCTION

Having an overall look to aircraft systems or analyze of a system-wide problem started to be very difficult as the avionics became more complicated and the interrelations between avionic subsystems rapidly increased. The work load dramatically increased on flight crews and maintenance personnel on the diagnosis of an aircraft system malfunction. For an unidentified failure, all related avionic equipments are required to be removed from the aircraft and inspected in maintenance hangar to find the root-cause of a single equipment. The unnecessary removal of avionic equipments increases the down-time of the airplanes in maintenance process.

On a system-wide malfunction, it is essential to locate the root-cause since many other interconnected subsystems may also give malfunction indications which can possibly hide the root-cause. Therefore, diagnosis techniques are applied to aircraft maintenance which collect data from sensors and computers and analyze them to identify the root-causes. An efficient diagnosis system decreases the down-time of aircrafts in maintenance hangar by decreasing the time to diagnose the failures.

Therefore, aircrafts' failures are needed to be processed in order to obtain a clear picture about the system's status to avoid more general system malfunctions which can lead to cancellation of the flight. In order to prevent these two consequences, modern aircrafts are implemented with various diagnostic maintenance tools such as *Build-in Test Equipments* (BITE) , *Central Maintenance Systems* (CMS), and *Fault Detection and Isolation* (FDI) tools.

There are multiple diagnosis approaches to an engineering systems which vary according to critical nature of the system. For example, a generator can simply check if the maximum temperature has exceeded the maximum safe temperature before shutting the unit down. However, same approach is unacceptable for a Boeing 777's *Turbine Gas Temperature* (TGT) monitor.

Today, it is widely accepted that the *model-based diagnosis* approaches are the best solution for aviation platforms which compares the observed aircraft status with a predicted model of failure/normal operation. However, a *model-based diagnosis* should contain a proper model that contains neither too accurate nor too simple operation/failure scenarios.

Model-based approach needs a well-defined operation/failure model which is supported by a wide range of scenarios. The designer can choose whether to model the normal operation scenarios or the failure operation scenarios of the system. There are three main model-based diagnostic modeling techniques which are named as *abductive* (failure scenarios) , *deductive* (normal operation) and *consistency-based* in which the model predicts the failure when normal operation is obstructed.

It is obviously more difficult to implement an *abductive* model to search for a root-cause in a centralized and integrated system. Because, the high number of shared sources and interconnections will eventually increase the number of possible failure scenarios. *Model-based* algorithm can be overloaded or can be short of fault scenerios. Therefore, *consistency-based algorithms* can reduce the suspected possible faults and leave the final decision to a fault-decision algorithm or even to a human operator.

This work firstly intended to provide background about *Central Maintenance Systems* (CMS) and it is major step back; highly interrelated avionics systems (computer control systems and architecture). Furthermore, a deeper analysis about *Fault Detection and Isolation* (FDI) is given since it is applied to CMS in root-cause search among avionic systems. In investigative part, the field research about FDI in a commercial maintenance company and an approach to FDI by using maintenance manuals and failure times are discussed. In conclusion, possible ways to improve FDI in maintenance hangar by using FDI tools are given.

1. PROBLEM STATEMENT & OBJECTIVES

Airline operation is a huge coordinated work which involves many different individual members such as dispatch, flight operations, maintenance, cargo, catering, legal office etc. Among all these, maintenance has a particular importance since it has direct connection with availability and sustainability of scheduled flights with strict time slots. “Time is money” is a very good description when we consider the maintenance on airline industry. Fig.1.1. shows the portions of individual services in airline operating costs [ATA 2005] where it can be seen that maintenance has 10% of all operating costs. A proper maintenance is affected by three major step backs [3];

- Highly interrelated and sophisticated avionics have tendency to suffer from complex failures which limit the technician’s exposure to a problem.
- Insufficient understanding about the avionic systems’ configuration.
- Unavailability or ineffectiveness of testing such as experienced technicians, user-friendly manuals, effective fault diagnosis equipment (FDI tools, BITE, field test equipments).

A proper fault diagnostics in maintenance directly affects two important operational parameter of airlines; *Dispatch Reliability* (DR) which basically shows the availability of flights and *Direct Maintenance Costs* (DMC) which gives the basic/mandatory repair costs [4].

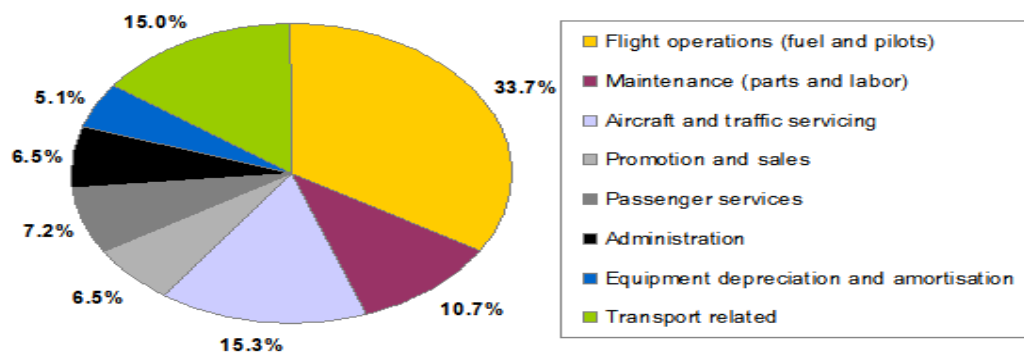


Fig.1.1. Airline operating costs (ATA Annual Report 2005).

When improper fault diagnostics is applied, the most undesired maintenance mistake , *No-Fault-Found* (NFF) increases the DMC and decreases the DR which primarily happens due to ineffective fault diagnosis while searching for the root-cause of the failure.

1.1 NO-FAULT-FOUND

NFF is the term when no failure is found in the avionic equipment after its removal and inspection. NFF can happen due to two reasons; First, the avionic equipment is actually no faulty but an interrelated faulty equipment caused its problem. Second, applied FDI tools or technicians are unable to locate the failure on the avionic equipment. One another reason for unidentified failures is the fact that some failures happen only when the aircraft is airborne due to enviromental conditions or other airborne effects. Therefore, an efficient FDI tool is critical to avoid unnecessary part removals in order to save time and money.

1.2 EFFECT OF FAULT DIAGNOSIS TO MAINTENANCE COSTS

The unscheduled avionic maintenance, in which an unexpected failure is fixed rather than its periodic maintenance, has the 18% of all DMC. Among 18% of DMC, 40% of avionic equipment removals result as NFF after the inspection in maintenance hangar [Boeing Airplane Group, 1998]. High ratio of NFF impacts the cost efficiency of the maintenance operation.

1.3 EFFECT OF FAULT DIAGNOSIS TO DISPATCH RELIABILITY

Dispatch Reliability (DR) is the ratio of alls flight to delayed or canceled flights due to technical problems. Fig.1.2. shows the major delay reasons where technical delays constitutes the 20% of all airline delays[3]. The costs of delays for various commercial aircrafts can be up to 20000 \$ per hour [Turkish Airlines 2009 Technical Report].

When the fault diagnostics are inefficient, technical delays happen frequently in flight operations when a scheduled or unscheduled maintenance takes more time then it is expected due to. During the delay, passengers have to provided by food and

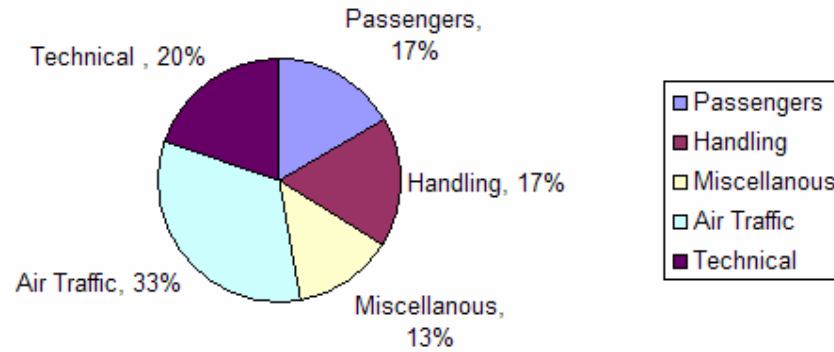


Figure.1.2. Percentages of delay reasons in airline operation (ATA 2005).

beverages and time-slot in the destination airport is missed. In case of unsolved failures in a determined time, the flight is canceled and the passengers have to be accommodated and transferred to another flight.

1.4 LITERATURE

The modern commercial airliners have highly interrelated avionics which use their own computer control systems [Moir I 2003, Yeh Y C 2001, McClarry C 1996, Hornish R R. 1992, Driscoll K 1992]. The interrelation of avionics in aircraft, “avionics architecture”, is necessary to understand for operational knowledge [James R W 2007, Peters M. 2003, Arinc 653]. The unnecessary down-times for fault isolation among interrelated avionics have a huge economical impact on airlines’ operational costs [Knotts R M 1999, AECMA 1989]. *Central Maintenance Systems* (CMS) are intended to gather all fault reports and provide a global approach to find the root-causes of failures [Bird G 2005, Roger K 1990, Felke T 1994, Arinc 624].

Presently, nearly all diagnostic approaches for engineering systems are based on *model-based diagnosis* after practical experiences in the past [Console L 1999, Cheng X 2003, Peisch B 2003]. According to completeness of the model, *Fault Detection and Isolation* (FDI) can be applied by using *abductive* or *deductive* reasoning [Rahmani S 1992]. *Abductive* approach requires the faulty model to interpret the best explanation or the most probable root-cause for a fault while *deductive* approach requires consistent observation and predictions [Poole D 1992].

In real world's practical diagnostic systems, the faults may have dynamic and time-varying behaviour [Console L 1997] which require a proper approach to model the aircraft for a good fault detection and isolation [Rahmani 1992] . In addition, practical systems may suffer from the need of real-time diagnosis of several faults which can most likely happen in an aircraft [Arjunan,M 1998, Jackson, E].

FDI applications require basic understanding about commercial airline maintenance [Demirci S 2009]. In addition, the approach to avionic equipment for FDI as a technician and maintenance programs of airlines should be considered in order to implement it properly [Demirci S 2009, Kinnison H A 2004].

1.5 AIM OF THE WORK

This research is the Master's Degree thesis of Electronics Engineering in Avionics area. The main objective, "Investigation of Aircraft Technical Diagnostic Systems", was taken as a base to understand the basic interrelated operation of avionics and *Central Maintenance Systems* (CMS). The logic approaches for *Fault Detection and Isolation* (FDI) in CMS are discussed in order to achieve the targeted tasks. Furthermore, the author seeks for solutions to improve avionics maintenance by presenting a FDI approach which was developed as a result of field research in a commercial maintenance company.

1.6 PRACTICAL VALUE OF THE WORK

Primarily, this work is intended to provide a wide perspective approach to *Fault Detection and Isolation* (FDI) in aircraft technical diagnostic by providing enough background about avionic computer systems which are FDI's main applied area. FDI is the key process in aviation maintenance and effects many other parameters of airline operation such as dispatch reliability, safety, cost effectiveness etc. Meanwhile, the research and analysis works would certainly provide a sequential knowledge about *Central Maintenance Systems* and their practical importance. The results of the analysis part is aimed to contribute to development of a FDI tool for commercial airliners' maintenance or certain proposes can be applied to existing FDI tools and improve their performance.

1.7 SCOPE OF THE WORK

This work is based on commercial jet airliners, mainly the Boeing and Airbus airplanes which are the leading manufacturers. The *Analytical Review* part is mainly based on Boeing 777 type aircraft since it has the most centralized architecture. Also, comparable informations about Airbus 330/340 are given in order to point their different architectural approaches. It is intended to provide readers with enough background such as *Computer Control Systems*, *Digital Data Buses*, *Avionic Architecture* etc. and then presenting the FDI basics such *Model-based Diagnosis*, *Central Maintenance Systems* etc. which are the applied to diagnose the given background about avionics.

The *Investigation and Analysis* part is mainly based on processes of aviation maintenance hangar's FDI (on the ground) and proposes a FDI technique which is intended to improve the maintenance hangar FDI. Note that, *Analytical Review* part provides onboard (on the airplane) FDI basics and systems. Investigations are done mainly in Boeing 777-300, Boeing 737-800 NG but a comparison is given by a short investigation in Airbus 320. The example proposed FDI analysis is given for a Boeing 737-800 NG airplane due to certain reasons such as documentation, popularity and complexity.

2 ANALYTICAL REVIEW

This part contains the necessary background to form the sequential flow of the research. *Computer Control System* (Part 2.1) is intended to provide the very basic operation of the aircraft computer systems while it is mainly focused on the interrelation and comparison between Boeing and Airbus (when available). *Central Maintenance System* (Part 2.2) is a brief description of CMS approaches and provides examples for various commercial airliners (B 747, Airbus 340, B 777). A brief information about *Digital Data Buses* (Part 2.3) is followed by *Architecture* (Part 2.4) mentions the way which avionic systems are connected and data collection by CMS. *Fault Detection and Isolation Methods* (Part 2.5) contains the theoretical background for FDI methods and provides additional information about practical issues of FDI applications.

Nature of Faults and Troubleshooting (Part 2.6) provides a fundamental approach to faults in aviation systems and gives the practical maintenance's *Fault Isolation* process which supports the research's intended FDI algorithm. Briefly, it contains basic information about the aircraft components' failure types, importance classification and aviation systems' troubleshooting (Part 2.6.3) which is prepared after a 2 weeks research in Turkish Technic company. In addition, the maintenance documents, which are basically the source of intended FDI application is also briefly described (Part 2.6.4).

2.1 COMPUTER CONTROL SYSTEMS

In commercial aviation, computers take place in basic needs of piloting such as tuning navigation beacons and communications, calculating cockpit indications and especially driving the flight controls properly. Even though there are various kinds of onboard computers such as *Display Management Computer* and *Fuel Management and Monitoring Computer* this part only covers the flight control system under four main sections; *Primary Flight Control System* (PFCS), *Air Data and Inertial Reference System* (ADIRS), *Automatic Flight Director System* (AFDS), *Aircraft Information Management System* (AIMS) and *Flight Management System* (FMS). All these systems work in high coordination and form the general *Flight Control System* (FCS) of the aircraft.

These systems are briefly described and comparisons are done between two major commercial airliners (Boeing vs Airbus). The main ideology and interrelation with avionic subsystems are mentioned in order to give an overall look to aircraft avionic system. *Central Maintenance System* (CMS) is given in separate section (Part 2.2) due to its high importance for aircraft technical diagnosis.

2.1.1 Primary Flight Control Systems

In general, *Primary Flight Control System* (PFCS) functions as a bridge between pilot's control commands or AFDS to aircraft's control surfaces to ailerons, elevators, rudder, stabilizer, slats and flaps. FCS determines the aircraft's attitude by using actuators to control the pitch, roll and yaw motions. In addition, aircrafts also have control surfaces called *Secondary Flight Controls* (SFC) to maintain stable flight by using elevator and yaw trims.

2.1.1.1 Boeing's Approach

Boeing 777's PFCS is ruled by three *Primary Flight Control Computers* (PFCC) each connected to related subsystems via three A629 data buses which is described detailed in following sections[1]. These three A629 data buses are named as Right, Left, Center and their interfering systems are shown in Fig.2.1.

As shown in Figure (2.1), PFCCs exchange information with AIMS (See Part 2.1.4) via A629 data bus in order to present control surfaces' situation to flight crew. ADIRS (See Part 2.1.3) provides aircraft's air and inertial data to FCCs for required processes again via A629 data bus. In automatic flight mode, AFDS (See Part 2.1.2) can also supply its control commands to PFCCs[5].

The important part of the system is the transmit of analog pilot commands and digital PFCC signals. *Actuator Control Electronics* (ACE) act as converter from digital to analog and otherwise[5]. By this means, two informations from pilot commands and PFCC respond can be processed and finally supplied to *Power Control Unit* (PCU) which gives the motion to drive the control surface[5].

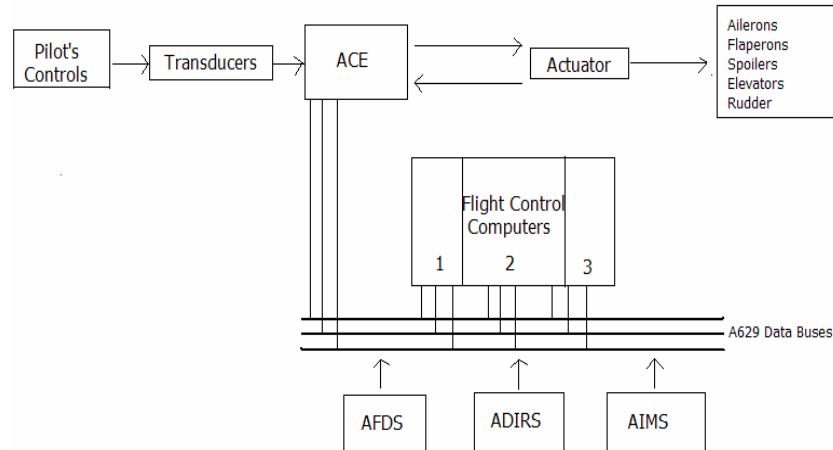


Fig.2.1. Boeing 777's Flight Control Computers and interfacing systems[2].

2.1.1.2 Airbus's Approach

Airbus A330 has three *Flight Control Primary Computers* (FCPC) which receive inputs from pilot's sidestick and *Flight Management Guidance and Envelope Computers* (FMGEC)[1]. FMGEC combines the functions of *Flight Management Systems* and *Automatic Flight Director Systems* which are described detailed in following sections. As a backup, two *Flight Control Secondary Computers* (FCSC) work in standby mode[1]. Two *Flight Control Data Concentrator Computers* (FCDC) gathers necessary information from flight controls to present in cockpit displays[1]. Lastly, two *Slat/Flap Control Computers* (SFCC) control the slats in leading edge and flaps in trailing edge. Fig.2.2. shows a general overview for primary flight control of A330's pitch and yaw motions.

Totally five computers are active for flight control of A330 where failure of two results to change from normal operation to alternate operation. The connection between flight control computers to flight surfaces are each controlled by a different actuator in order to enhance safety. Also, the actuators of each control surface are controlled by different computer to prevent the loss of entire control surface.

2.1.2 Autopilot Flight Director Systems

The necessity to assist pilots for increased workload of aircrafts brought the *Autopilot and Flight Director System* (AFDS) to provide automatic commands to flight surfaces in order to guide the aircraft in a selected path.

Due to its autonomy, AFDS requires data and guidance information from many sensors and computers while maintaining automatic flight. These informations can be entered manually from pilot's *Control Display Unit* (CDU) or gathered from aircraft's sensors such as VOR/ILS or vertical/directional gyros. An overview for Boeing 777 AFDS system is given in Fig.2.3.

In Boeing 777, three (right, left, center) *Automatic Flight Control Computers* (AFDC) provide triple redundant structure to transmit control commands to *Primary Flight Control System* (PFCS) in order to drive the *Actuator Control Electronics* (ACE) of the desired flight control surfaces[8].

AFDCs have triple redundant connection and multi-channel control for achieving fail-operational autolands and automatic approaches[1]. In addition, each AFDC receives redundant sensor data and has cross-communication with other AFDCs[6]. The control commands of AFDCs are then checked in *Primary Flight Computers* (PFC) according to their acceptability such as *g restrictions* or *ailerons exceedance* to be applied as a control command to ACE[8]. The overview of AFDC's redundant structure is briefly illustrated in Fig.2.4.

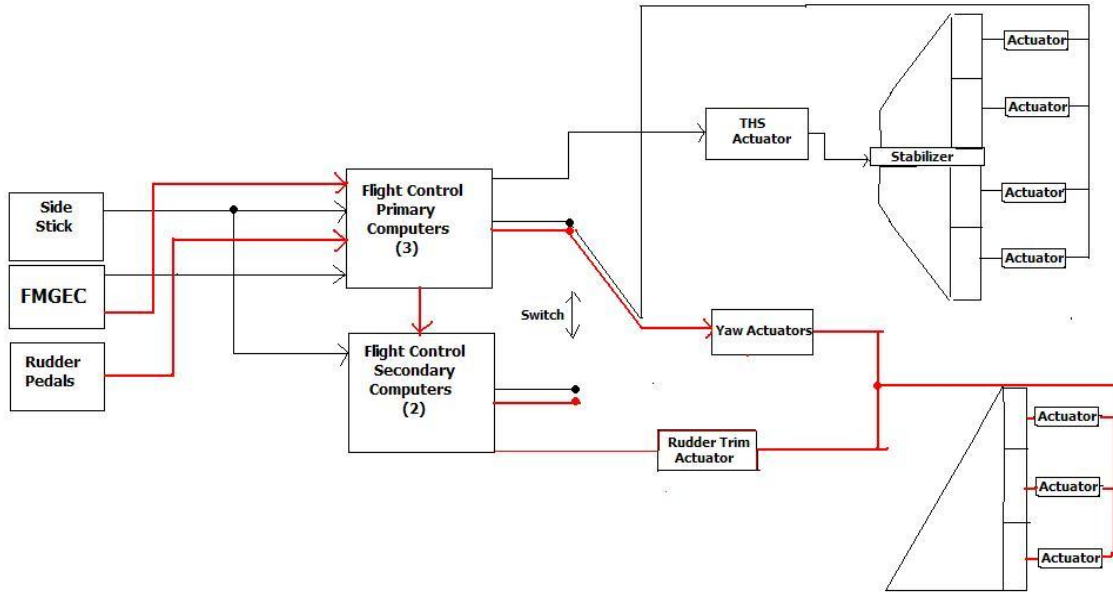


Fig. 2.2. Airbus A330's Primary Flight Control System[6].

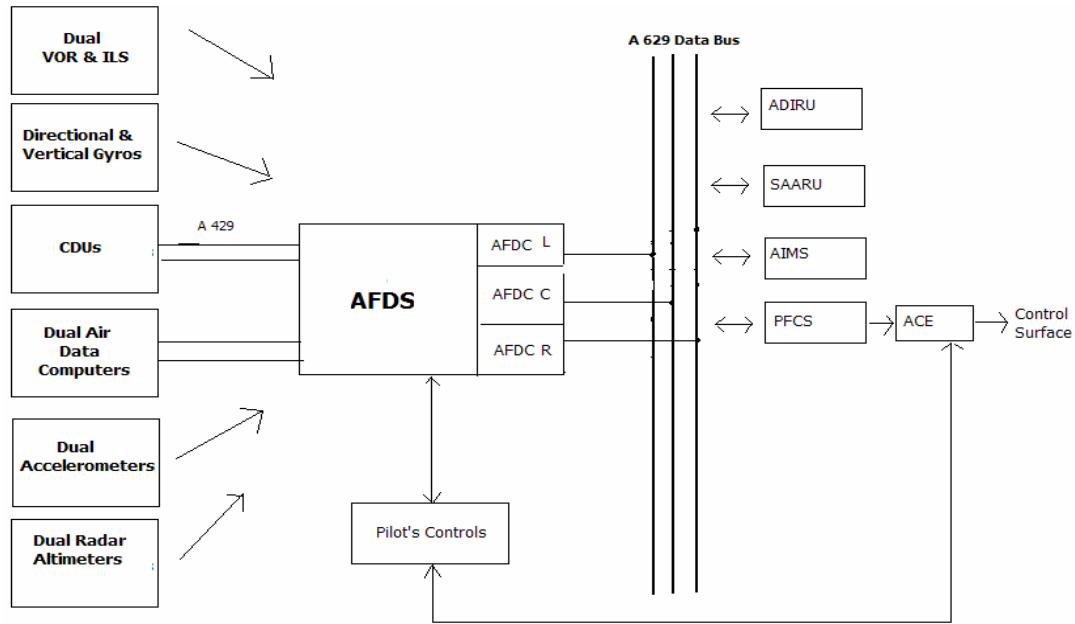


Fig.2.3 AFDS's connection with other systems and sensors [1].

2.1.3 Air Data and Inertial Reference Systems

Air Data Measurements (ADM) are performed by using pitot pressure, dynamic pressure, pressure change, and outside temperature readings. These senses are processed and computations are done in order to display; *barometric altitude*, *vertical speed*, *indicated air speed*, *true air speed* and *static air temperature*. These parameters are used not only in navigation systems but also in flight control, engine control and many other subsystems[1].

Inertial Reference System (IRS) mainly supplies the onboard *Inertial Navigation System* (INS) sensors which performs the navigation without radio-aids. Due to high calculation complexity, two or three INS modules are used in aircrafts to achieve better accuracy[1].

System designers combined the functions of ADMs and IRS to achieve comparative reliable system and produced *Air Data and Inertial Reference System* (ADIRS)[5]. Most recently, *Fault Tolerant Air Data Inertial Reference Systems* (FT/ADIRS) brought better reliability[7].

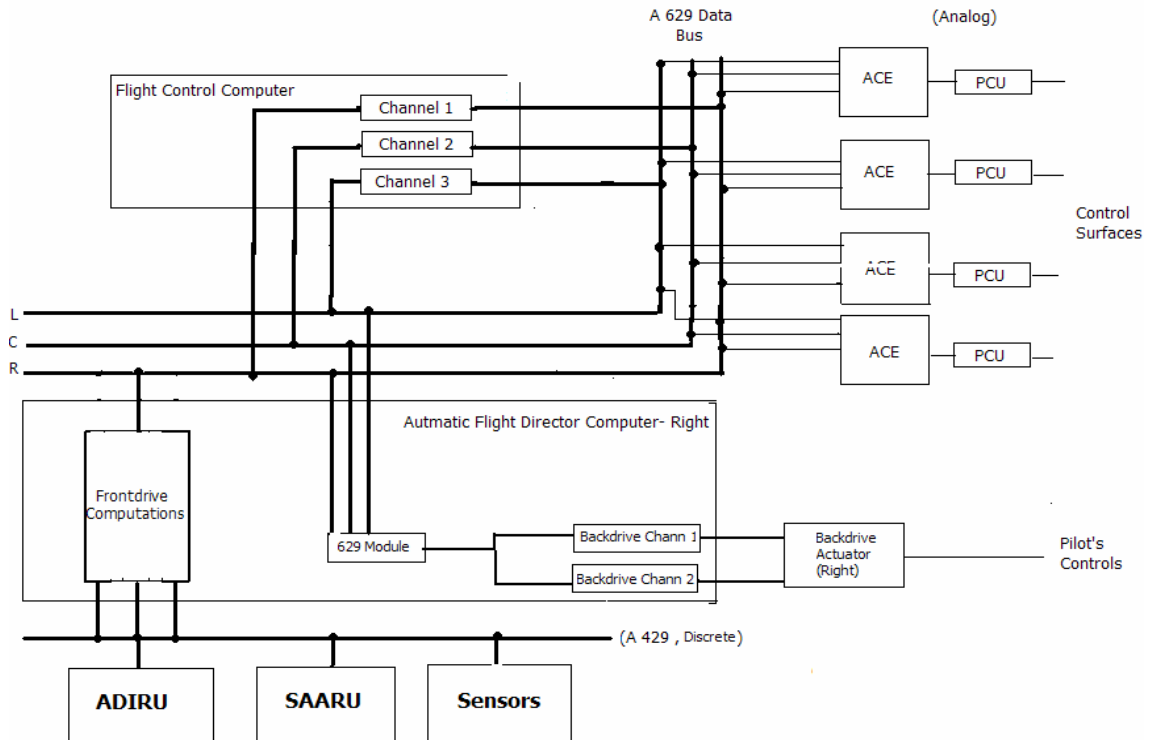


Fig.2.4. Illustration of right AFDC's fail-safe connection with PFCS.

FT/ADIRS system is based on *fault tolerant electronics* and redundant sensors[7]. The parts of the system are *Air Data Inertial Reference Unit (ADIRU)*, *Secondary Air Data Inertial Reference Unit (SADIRU)* and the ADMs for pitot tubes and static ports, angle of attack sensors, total air temperature sensors. SAARU provides data for standby flight displays[7]. Overall system example for a Boeing 777 is shown briefly in Fig.2.5.[7].

ADIRU architecture also provides electrical and physical separations to isolate possible malfunctions in *Fault Contamination Modules (FCM)* within each part of ADIRU[5]. In Boeing 777, *Fault Contamination Areas (FCA)* isolates the parts of ADIRU between each other to achieve greater fail-safe structure. In Airbus approach, four MCU ADIRU are used for fail-safety instead of Boeing's fault tolerant connection solution[1].

2.1.4 Aircraft Information and Management System

High data rate and modular avionics need for easier maintenance brought the centralized redundant control and integration of total information by *Aircraft Information and Management System* (AIMS) with the Boeing 777. The main idea behind the AIMS is to accommodate\ all avionics where they can share the same common sources such as power supply, mechanical supply, I/O modules, data bus, processors and operating software[9].

AIMS consists of two identical (redundant) cabinets, each shares four *Core Processor Modules* (CPM) and four *I/O Modules* (IOM) which are *Line Replaceable Units* (LRU)[9]. Each cabinet hosts certain avionics modules; FMS, displays, navigation, central maintenance, flight deck communications, thrust management, digital flight data, engine data interface and data conversion gateway[1]. Each cabinet has one CPM and two IOM reserved places for possible additions to AIMS[1].

AIMS interfaces with other aircraft systems via four A629 (Systems data buses), three A629 (Flight control data buses), A429 data buses and many other discrete or analog connections. A general overview for AIMS is given in Fig.2.6.

The extensive data load from aircraft systems and avionics modules can be assembled together according to one basic rule that no failure in a function causes another function to fail[9]. To achieve this, AIMS has a robust partitioning architecture that functions use common sources without interacting to each other by using scheduled time slots to reach common sources. A database of time schedule tables controls the timing of all data transfers so that only one function can gain access to AIMS common memory at a time[9].

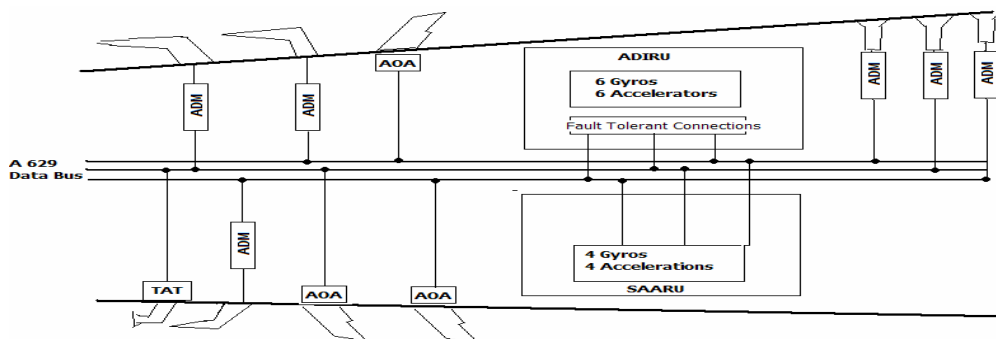


Fig.2.5. FT/ADIRS of Boeing 777[1].

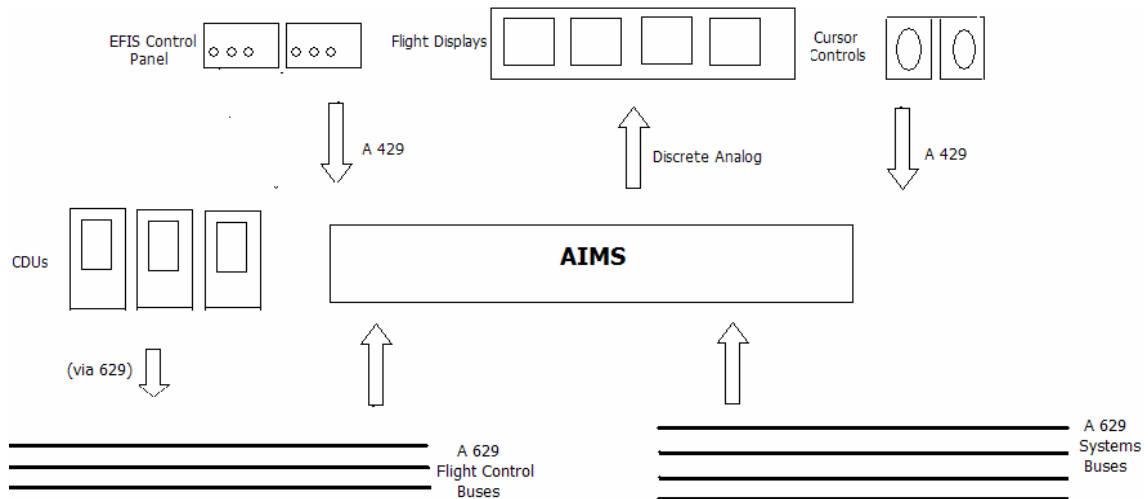


Fig.2.6. AIMS and its interfacing systems.

2.1.5 Flight Management Systems

Air traffic complexity, high communications need and long flight routes brought the need for a management system to deal with navigation and communication issues of aircraft. Thus, *Flight Management Systems* (FMS) process the necessary calculations and organize the sensor informations to provide guidance to overall flight path of the aircraft[1]. FMS also provides guidance to tune to necessary communication and navigation beacons during the flight.

FMS consists of; dual *Flight Management Computers* (FMC), dual *Multi-functional Control Display Units* (MCDU) and connected sensors those provide information about attitude, navigation and aircraft systems informations[1]. A general overview of the system is given in Fig.2.7.

FMC conducts the computations by using integrated models and database with gathered sensor information. The various inputs from connected systems and the database information is used to obtain a proper flight path for aircraft.

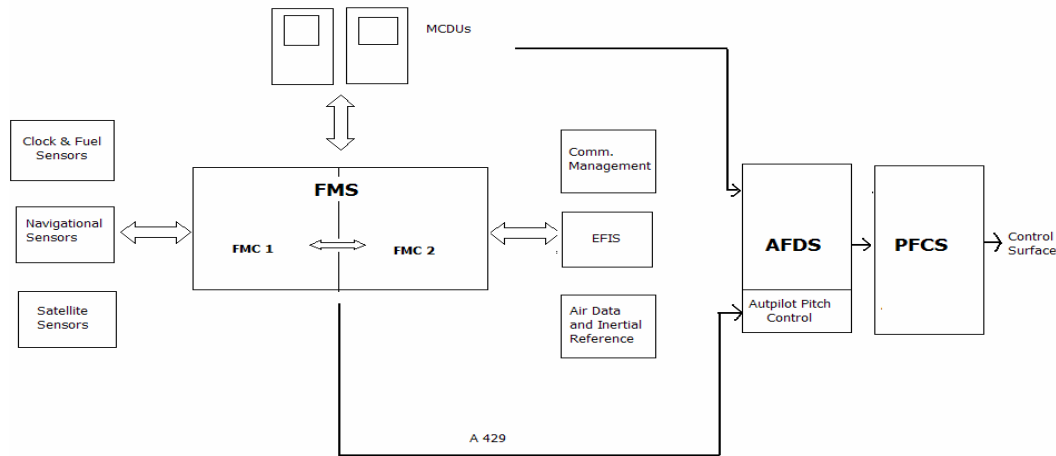


Fig.2.7. FMS and its interfacing systems

2.2 CENTRAL MAINTENANCE SYSTEMS

Since commercial aviation should keep its airplanes operational to cover the strict flight schedules, it is very important to reduce the down-time for maintenance purposes. In earlier times, investigation of a reported “hard landing” used to require removal of air data collection unit from aircraft by a technician, extracting large amount of data to ground unit, analyze of the data to confirm the reported “hard landing” and finally the process to search for possibly damaged components by checking system’s individual *Build-in Test Equipments* (BITE).

The primary purpose of *Central Maintenance Systems* (CMS) is to assist the process of fault analysis by gathering BITE information from a single source without being have to investigate whole aircraft. Thanks to CMS, the status of aircraft can be checked just after seconds of the hard landing and if it is confirmed, possibly damaged components can be reported immediately to maintenance personnel.

However, addressing the source of a malfunction is a quite complicated task when we consider the enormous number of related systems existing in today’s airplanes. The possible causes and its effects can be related to any subsystem of the malfunctioned system. Therefore, *Central Maintenance Computers* (CMC) process the data gathered from entire airplane to precisely address the root-cause of the malfunction.

The final and the core part of onboard maintenance is to run a effective *Fault Detection and Isolation* (FDI) model which actually searches for the root-cause of the problem from a large number of possible fault indications and isolate it. FDI approach should be compatible to aircraft's architecture. FDI model runs with a software and the approach to establish the model constitutes the most important part due to its complexity to analyze and insert to model the aircraft's possible faults[20].

2.2.1 Build-In Test Equipment

Due to microelectronics applications in avionic systems, addressing a fault in electronic cards is nearly an impossible task for maintenance personnel. Therefore, a module in every LRU called BITE monitors its own system and make diagnosis to find the faulty part. BITE has eliminated the complicated avionic system tests and make it possible to find out a LRU's fault without removing it from aircraft to maintenance workshops.

BITE can be applied continuously (CBIT) or can be done during pre-flight checks (IBIT). Nowadays, the CBIT information of individual avionics are supplied to a central system in real-time thanks to high rate data buses such as A 429 and A 629. Therefore, flight crews are able to see continuous updates of the system[2].

2.2.2 Central Maintenance Computers

CMC collects the fault reports from each member LRU's own BITE and analyzes them in order to present a picture about the aircraft's situation. More importantly, CMC engages to prevent/isolate an individual malfunction to cause a more general system function. Finally, it addresses the root-cause of problem and informs the crew or maintenance with advisory information and troubleshooting assistance.

A guidance document called ARINC 624, which is prepared by global ARINC organization, provides all necessary information to design a OMS system for a commercial aircraft. The document covers CMC and also *Airplane Condition Monitoring System* (ACMS) specifications. OMS system architecture is given in Fig.2.8. according to ARINC 624 report.

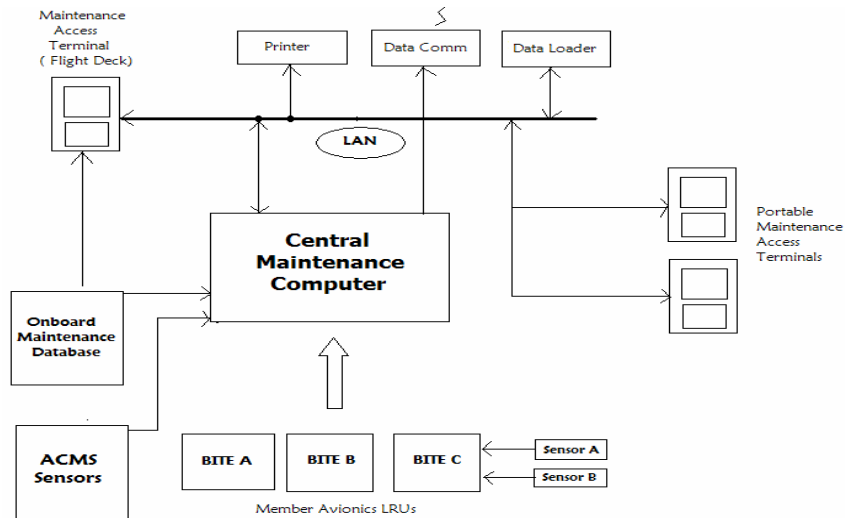


Fig.2.8.ARINC 624 OMS overview[ARINC 624 Report].

The basic tasks expected from a CMC are as follows[2,8]:

- Fault Detection: Being aware that one or more systems in the aircraft have failed or in abnormal operation.
- Isolation: Identifying the root-cause of the problem.
- Correlation with Flight Deck Effect: In order to isolate a failed component, CMC reflects indications on flight deck to inform pilots.
- Storage and Report: Keeping the necessary fault history or maintenance data for further analyze.

In following parts, Boeing 747's CMC, Boeing 777's *Central Maintenance Computer System* and Airbus A330/340's *Central Maintenance System* (CMS) is given for a comparison of OMS evolution and different approaches..

2.2.3.1 B 747-400's Central Maintenance System

Before B747-400's CMC, all individual avionic LRUs were responsible for their BITE and isolation of their malfunction. Then, fault reports were sent to central system only for presenting a total display for flight crews.

In B 747-400's CMC, individual avionic LRUs are still responsible for maintaining BIT but the isolation decision and further processes are done in CMC in order to have a total control for aircraft.

Boeing 747-400 CMC was able to conduct following operations[20]:

- Identifying faulty system part and isolating it.
- Keeping aircraft's fault history in its storage.
- Serving as common collection and retrieve point for all maintenance data.
- Providing assistance for troubleshooting with its huge library
- Prepares raw data for effective down-link via ACARS.

2.2.3.2 A 330/340 Central Maintenance System

Airbus uses a similar approach to B 747-400's CMC and it highly utilizes from A429 data bus to gather larger amount of diagnose data from aircraft and evaluate them in dual CMC. System also can connect to subsystems via discrete connection rather than A429 data buses. The connection way is based on classification of avionic LRUs in three types: Type 1 LRUs connect to CMC only through A429 buses, Type 2 connects through a discrete cables and A429 bus, Type 3 connects through only discrete cables[2].

Like nearly all OMS, A 330/340 also uses MCDUs to monitor system status or to reach maintenance functions of CMC. A different approach of Airbus enables to analyze fault history from sensor level to shop level in order to parts with previous fault history can be identified to make a better diagnosis[1].

2.2.3.3 B 777's Central Maintenance System

Boeing's approach to central maintenance is more onboard integrated and has the advantage to utilize from A620 data buses to reach aircraft systems. It uses a separate display called *Maintenance Access Terminal* (MAT) for access of maintenance personnel instead of using CDUs. However the most significant difference is that the information collection is done by *Aircraft Information Management System* (AIMS) where CMC resides inside[1].

2.3 DIGITAL DATA BUSES

Complex computers systems and increased number of sensors demanded a reliable method to exchange data, command and status information between avionics. Avionic systems and subsystems communicate with each other by using special protocols which are designed to fulfill the airborne requirements whether it is a commercial airliner or a advanced jet fighter. Therefore, special protocol standard which are named as ARINC 429, ARINC 629, MIL-STD-1553 are the primary digital avionic data buses in commercial jet airliner and military aircrafts whereas new standarts such as AFDX is proposed to provide much better performance.

The data bus standards show differences with respect to applied airborne platform where the performance expectances are different as well. The specifications to consider an avionic data bus are as follows[2]:

- Data transfer way: Simplex (Single transmitter, multiple receivers) or Duplex (Multiple transmitter, multiple receivers).
- Transmission media as wire or optical cable.
- *Bus Control* structure.
- Speed (Bit rate).
- Message structure.

Without a doubt, ARINC 429 is the dominant data bus in commercial airliners and even used in some applications of military aircraft because of its well-established and cheap technology. Similarly, MIL-STD-1553 is used in various military applications thanks to its highly reliability despite of its moderate cost. On the other side, Boeing 777's primary data bus, ARINC 629 offers excellent reliability and speed performance, however it has not been used in any other aircraft for certain reasons which are discussed in Part (2.3.4)

This part briefly describes the avionic data buses due to fact that they are the key player in FDI by either determining fault propagation and data transfer. As an example, ARINC 429 specifications are given detailed, due to its wide usage in avionics, with a comparison with a brief description for ARINC 629's time-division protocol. Furthermore, MIL-STD-1553's properties are briefly given. Lastly a discussion part generally compares the three main digital data buses.

2.3.1 ARINC 429

ARINC 429 is a well-known, widely used avionic data bus which uses one-way broadcast (simplex) where transmission are done in a single connection with a single transmitter which is able to broadcast up to 20 receivers[21]. It has very slow bir rate compared to other standards which can be 12 Kbps or 100 Kbps depending on application.

2.3.1.1 Electrical Characteristics

Data words are transfered by varying the potential between two wires and padding zero voltage between words in order to separate them without need for a clocking signal[21]. A +10 V (between +7.25V and +11 V) potential should be observed in receiver in order to interpret it as “HIGH” which is done by applying +5 and -5 V in two wires. Similarly, “LOW” requires a received signal between -7.25 V and -11 V. Zero voltage, “NULL” is received when reception potential is between +0.5V and -0.5 V. A simple encoding example is shown in Fig.2.9.a.

2.3.1.2 Word Format

Data words consist of 32 bits which are partitioned as shown in Fig.2.9.b. Five partitions are; a parity bit, two *Sign/Status Matrix* (SSM) bits which shows the condition of the component, data bits between 29-11 contains the data information, 10th and 9th bits are *Source/Destination Identifier* (SDI) bits which is used to address the location of multiple receivers (maximum 20) and bits between 8-1 are the label bits which identify the data type (Described in next part)[21].

2.3.1.3 Data Types

The 32 bit data words can be classified as *Binary Coded Decimal* (BCD), two's complement *Binary Notation* (BNR), discrete data, acknowledgement or maintenance data[21]. For example, Fig.2.10. shows the transmitted DME data which shows the distance as 25786 by a BCD data.

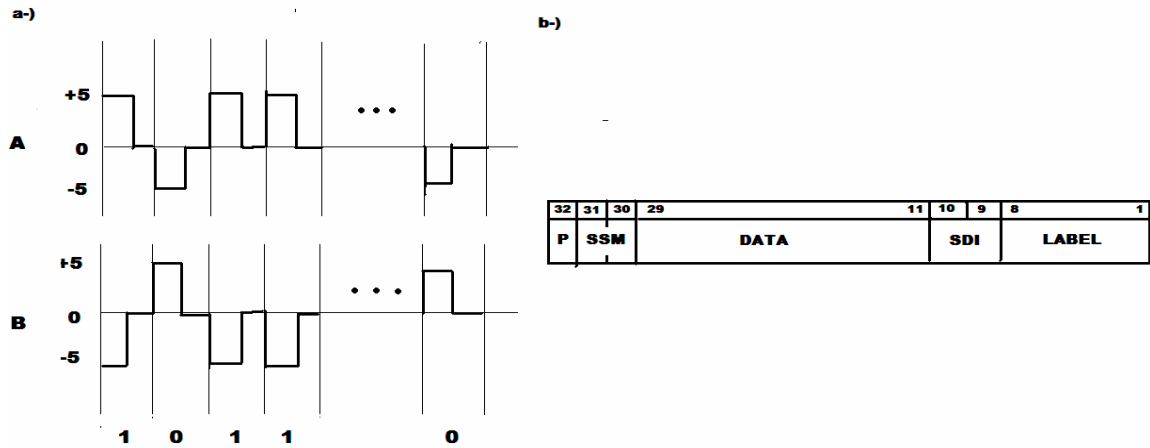


Fig.2.9. a-) Bit encoding example for A 429 b-) Data word partitioning of A 429.

32	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	1
P	SSM		0	1	0	0	1	0	1	0	1	1	1	1	0	0	0	0	1	1	0	SDI		LABEL	
	0	0	2			5			7			8			6										

Fig.2.10. A 429 standard BCD data of DME distance.

2.3.2 ARINC 629

A 629 is a multiple-transmitter and multiple-source digital data bus that is to say every connected member can transmit and receive information to data bus. Furthermore, it can accommodate 128 terminals with a data speed of 2 Mbps while A 429 can accommodate 20 terminals with 100 kbps in a single data bus line[2].

Its quadruple, triple and dual data lines provides redundancy to system which they are applied to according to its importance (See Fig.2.11.). For example, engine controls are done over a quadruple data bus while *tire pressure control* is connected to dual redundant data bus[1].

2.3.2.1 Protocol

Data transfer is done over a time-allocated system such that each terminal can transmit data to bus only in a specified time intervals[22]. The *Transmit Interval* (TI) is the time that bus is open for all terminals to send their messages and it is typically

0.5 ms or 64 ms. *Synchronization Gap* (SG) is the time interval when bus is ensured by *Bus Quiet* test that all terminals have transmitted their data and it has 17.7 μ s, 33.7 μ s, 65.7 μ s and 127.7 μ s values according to application. *Terminal Gap* (TG) is specific time for each terminal from 3.7 μ s to 127.7 μ s and it is the time interval before the associated terminal will start transmitting. Figure (3.3) illustrates the A 629 time division protocol for a three terminal situation (Actual system accommodates much more) [22].

2.3.3 MIL-STD-1553

Similarly to A 629, MIL-STD-1553 also employs a time-allocated multiplex data bus architecture for data transfer with a major difference that bus activity is controlled by a single component rather than transmitting terminals themselves[23].

MIL-STD-1553 transmits 20 bit words with 1 Mbps speed which is faster than A 429 but significantly lower than A 629. The system employs three types of terminals; one or two (redundant) *bus controllers* (BC), *remote terminals* (RT) and *bus monitor* (BM). BCs determine and send orders to RTs about which messages they should send. RTs accommodate several avionic LRUs (Line Replaceable Unit) and permits their message to enter data bus according to messages from BC. BM is used to detect the activities in data bus and report them periodically. Fig.2.12. briefly illustrates a quadruple redundant MIL-STD-1553 data bus architecture[23].

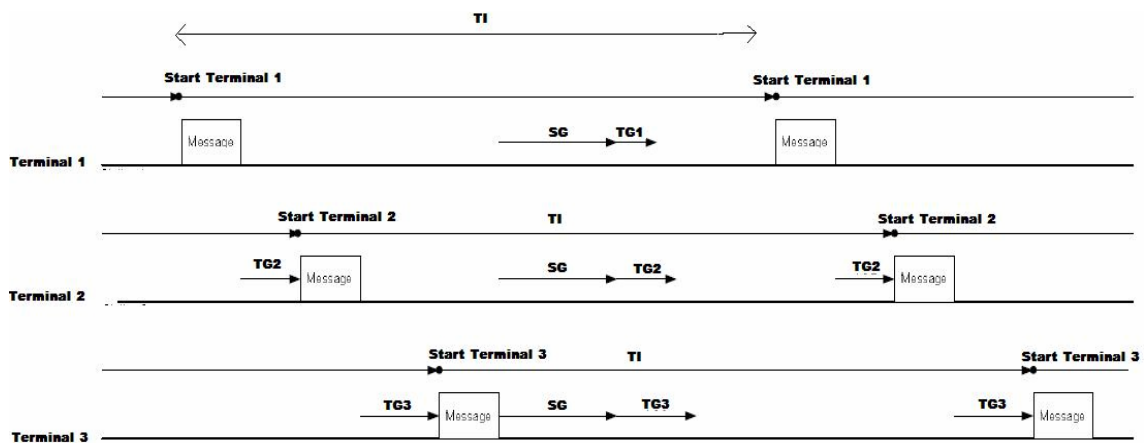


Fig.2.11.ARINC 629 protocol. (Recreated from the Figure of [22])

2.3.4 Discussion

Even though A 429 has the lowest speed and robustness among all digital buses, it has the largest application area thanks to its 30 years old proven technology. The key point that makes A 429 dominant is its simplicity which is very important in certification of avionic architecture. The major step back about A 429 is the possible integration problems such as *Source/Destination Identifier* (SDI) orders when a new avionic system is added to architecture[24]. In addition, the avionic architecture should be able to tolerate the data collision possibilities of A 429[2].

When it was introduced in 1990s, A 629 proposed as a new trend for avionic data buses. It is significantly superior to A 429 by speed and performance while it eliminates the *Bus Controller* which is considered as the weakness of MIL-STD-1553. However, the cost and to detect the activities in data bus and report them periodically. Fig.2.12. briefly illustrates a quadruple redundant MIL-STD-1553 data bus architecture[23]. Complexity of A 629 architecture eventually eliminated it from the digital data buses area while even Boeing is using a very fast Ethernet connections in its new B-767 and proposed B-787 aircraft.

Since *Analytical Review* part primarily focuses on B-777 and A-330/340 aircraft, information about A 429 and A 629 is mainly provided. However, it is obvious that new digital data bus trend is very fast Ethernet connection named as *Avionics Full-Duplex Switched Ethernet* (AFDX) in new jet airliners such as B-787 and A-380.

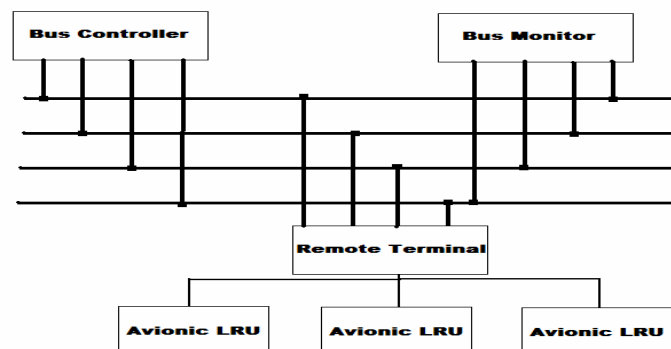


Fig.2.12. A quadruple redundant MIL-STD-1553 connection example.

2.3 ARCHITECTURE

Crossing the Atlantic Ocean in a precise route or landing in a CAT III condition airport requires a highly coordinated work of avionic subsystems by sharing the real-time information between each other. Whereas, systems such as *Autopilot Flight Director System* (AFDS) and *Flight Management System* (FMS) are actually combination of various subsystems which are integrated together to achieve better navigational performance.

The interconnected and integrated avionics brought the concept of *avionic architecture* which targets to combine individual avionics subsystems or even systems in a common place where they share the common resources such as power supply, processor or even operating system in order to achieve the targets as follows[11]:

- Save weight by reducing wiring, power supplies etc.
- Reduce power dissipation by using common source.
- Monitor overall system from a single point of view.
- Reliability by using common redundant sources.

However, avionic architecture requires a reliable and fast data transfer method between components due to high amount of necessary exchange for coordinated operation such as *Primary Flight Control System* (Part 2.1.1) . Therefore, digital data buses such as ARINC 429 (for many civil aircraft), ARINC 629 (Boeing 777) and MIL-STD-1553B are utilized in order to increase the throughput of the data transfer.

Even though, both Boeing and Airbus produce aircrafts for almost same purposes with correspondent systems, their approaches for avionic architecture significantly differ (Boeing 777 and Airbus A 330/340). The main differences between Boeing and Airbus structures are centralized approach of avionic LRUs in Boeing 777's AIMS (Part 2.1.4) and the utilization of data buses which separates them as a "centralized" and "distributed". This part presents the evolution of avionic architecture and describes the new conception of *Integrated Modular Avionics* (IMA) which certainly should be considered in new *Fault Detection and Identification* (FDI) systems.

2.3.1 Evolution of Avionic Architecture

Early times of avionics utilized electromechanical instruments and had completely independent (separated) avionic systems which had their own analog computers, power supplies and indicators as shown in Fig.2.13.a Different purposed systems had no information transfer between but only single, point-to-point information transfers were done. Introduction of *Flight Management System* (FMS) (Part 2.1.5) brought the first centralized approach as seen in Fig.2.13.b [12].

Firstly, FMS combined the information from navigation, air data etc... and presented a centralized picture to pilots. By the introduction of INS and many other supportive systems, avionics needed to be control as more centralized as it can be. *Federated* avionic architecture (See Fig.2.14.a) started the concept that every LRU conduct its own operation while they are monitored and engaged by a central processor when it is necessary.

However, central processor gathers high amount of data from connected LRUs and it should sent back data to important LRUs with a necessary speed. This brought the necessity for a fast and reliable connection and consequently digital data buses were introduced. Final conception is the *Integrated Avionics Module* (IMA) (See Fig.2.14.b) where many avionics are placed in the same cabin where they share common sources.

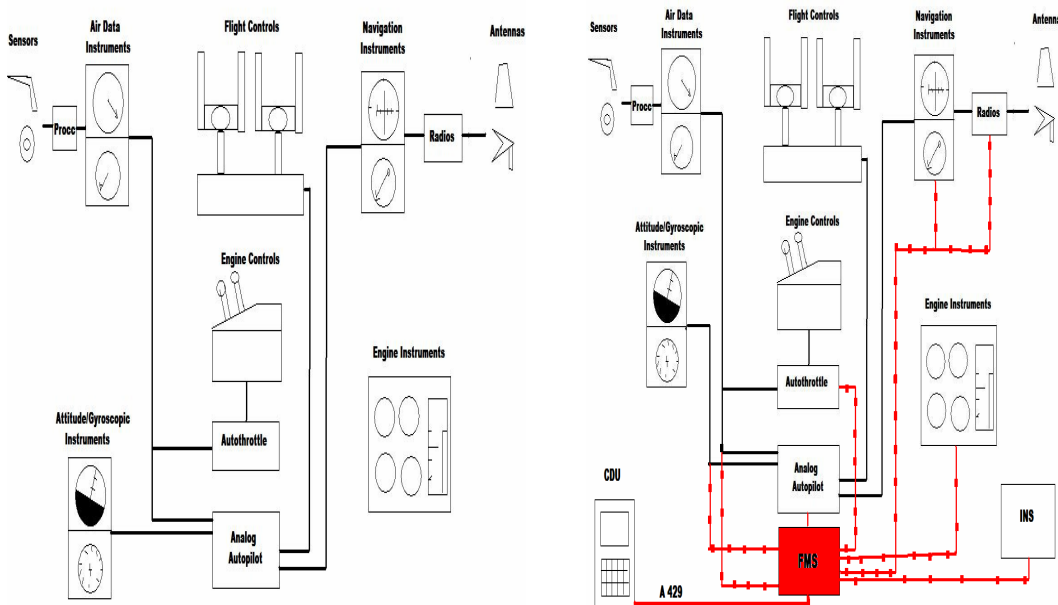


Fig.2.13 a-) Electromechanical independent architecture. b-) Electromechanical architecture with FMS.

2.3.2 Integrated Modular Avionics

Present avionic architecture of an aircraft is considered as a *network* where high amount of data is exchanged in order to maintain highly coordinated processes. The challenges which newer aircrafts are facing in order to achieve reduce space, weight and power dissipation are as follows[10]:

- Multiple applications are embedded in single hardware.
- More complicated therefore larger software in processors.
- Complexity of software coordination.

Therefore, *Integrated Modular Avionics* (IMA) is a new concept that replaces numerous processors and LRUs with a common control unit where resources are shared in order to have a more efficient network compared to *federated avionics*. For example, instead of placing individual power supplies in every LRU which can be possibly malfunctioned, a single redundant and reliable power supply is used to prevent individual LRU failures[12].

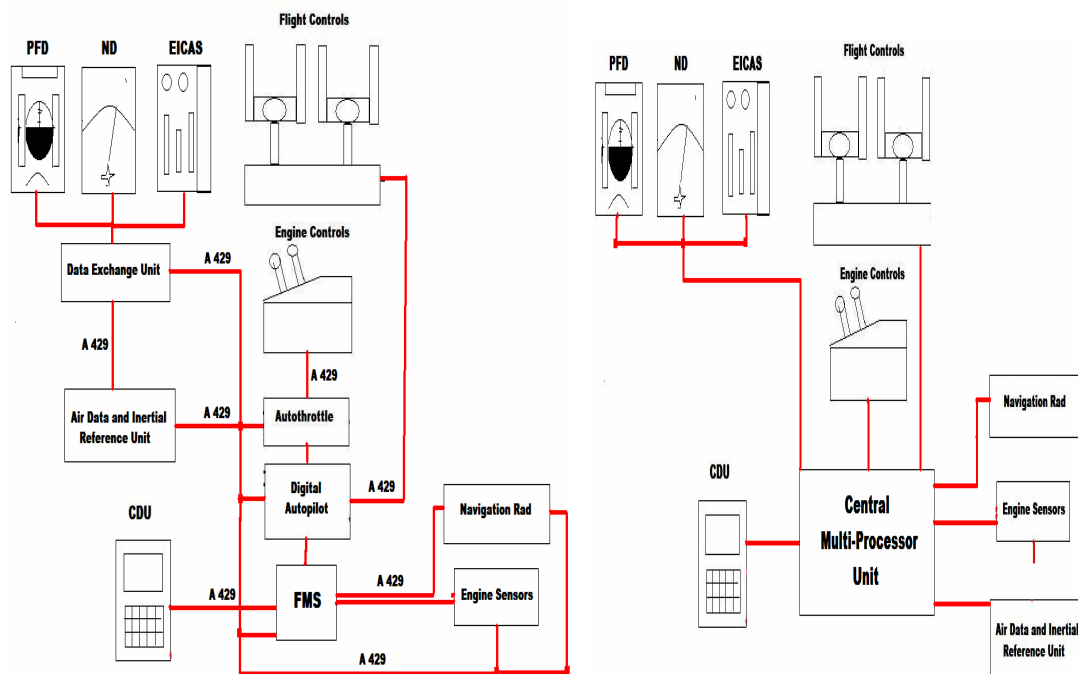


Fig.2.14. Federated Digital Avionics versus Centralized IMA Architecture.

The most important feature of IMA is the usage of *Application Layer Software* (API) which replaces the function of hardware with software and makes it easier to conduct upgrades or system integration as well as the maintenance [11]. The API design for airborne systems are standardized under ARINC 653 standard and it allows to host multiple applications of different software on the same hardware in the context of a IMA architecture[10].

AIMS cabinet in Boeing 777 can be considered as the first IMA application while new designs such as Boeing 787 and Airbus 380 utilize a more IMA architecture by integrating more aircraft functions into a cabinet where they use common sources[11]. Boeing's *Common Core System* (CCS) combines aircraft functions in a single cabinet by applying ARINC 653 partitioning and utilizing of *Full Duplex Switched Ethernet* (AFDX) data bus[11].

However, this Master's Degree thesis covers the avionic architectures of Boeing 777 and Airbus 330/340 due to the fact that Boeing 787 and A 380 are very new systems which have not conducted their maiden flights yet.

2.3.3 Boeing's Approach

Boeing 777 uses centralized common, multi-point ARINC 629 data buses which are named as *Systems Buses* (four), *Flight Control Buses* (three) and also some number of point-to-point ARINC 429 data buses (See Fig.2.15)[2]. Data collecting function is carried out by AIMS, where all integrated avionics share the same sources such as power supply, I/O ports, processors, common software etc...

2.3.4 Airbus's Approach

In Airbus approach, systems are connected through point-to-point ARINC 429 data buses or/with some analog connections. This leads to that systems may have only single connection with each other. For example; the heart of *Fault Detection and Identification* in A 330/340 aircraft, the two *central maintenance computers* (CMCs), collect the necessary data from connected LRU's BIT equipment directly by A 429 connections and some analog connections. Individual avionic LRUs have their own power supplies, processors and operating systems (if installed). CMCs connection with surrounding BIT equipments are briefly illustrated in Fig.2.16. [1].

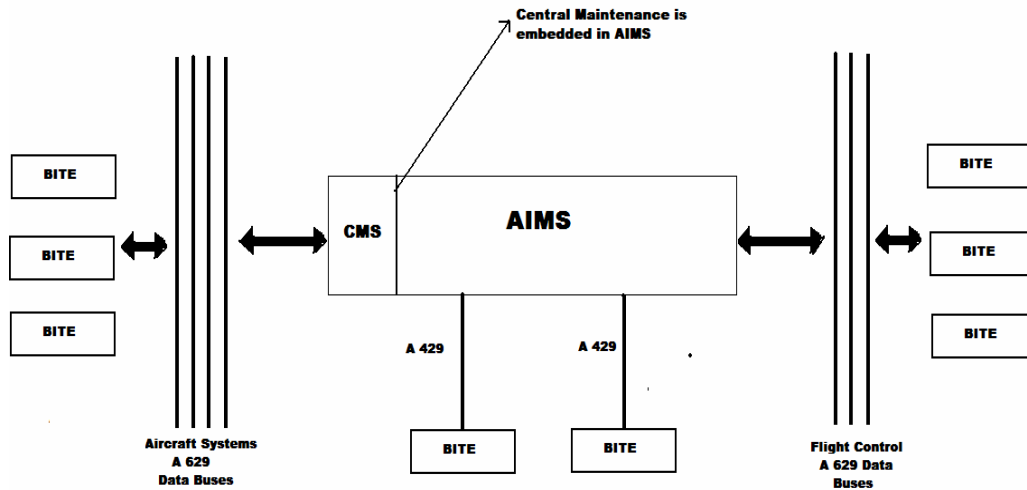


Fig.2.15. Airplane Information Management System of Boeing 777.

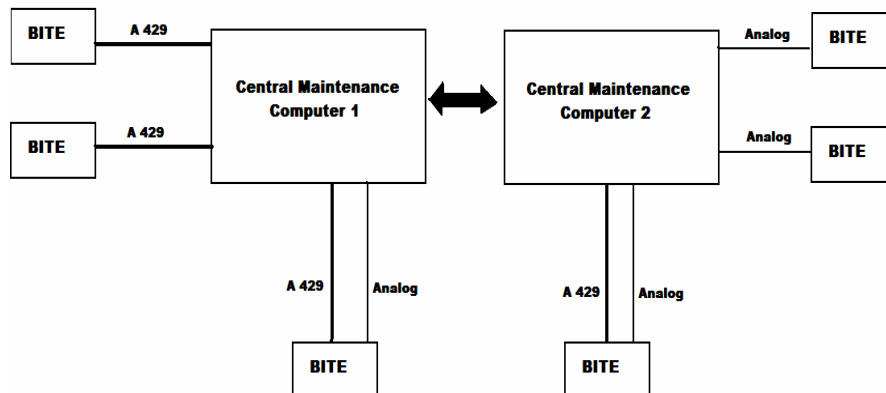


Fig.2.16. An example for point-to-point architecture of center maintenance system of Airbus 330/340.

2.4 FAULT DETECTION AND ISOLATION METHODS

Avionic architecture consists of many interrelating systems which may have critical effects on flight safety. A single component failure in a avionic device may propagate and cause a total system failure if it can not be detected and isolated. Therefore, the primary purpose of FDI is to provide capability of early fault detection and isolate them before they become a critical system problem.

FDI model constitutes the brain of CMC which contains the fault analysis algorithms that is specified for the certain system. The model contains fault conditions, associated symptoms and corrective actions for each LRU in the aircraft[15]. Following parts briefly give FDI model approaches and some concepts those are necessarily to know to understand the CMC's FDI model.

2.4.1 FDI Characteristics

FDI has three major functions to avoid a system damage or propagating fail when they sense an abnormality in the given system. Following functions are dependent on the necessary simplicity-accuracy trade-off[28].

- *Monitor*: Variables are compared with regard to system limits and fault information is supplied if there is exceedence.
- *Automatic Protection*: In case of a exceedence between variables and limits, system automatically applies a corrective action.
- *Supervision with Fault Diagnostics*: In addition to previous functions, a fault diagnosis is made and symptoms are generated to supply to user.

Early BITEs were performing *Monitor* function that only a “GO” or “no-GO” indication were supplied to maintainers or flight crews on behalf of FDI. Then, visual inspection or manual tests were applied to diagnose the fault. Automatic shutdown of a aircraft generator due to unstability would not show the root-cause of problem but it is able to prevent a further problem related to generator. However, today's avionic systems obviously require a *Supervision with Fault Diagnostics*.

A FDI process consists of three sequences those are necessarily should be correct to confirm each other[28]:

- *Fault Detection*: Indication that there is abnormality in the system.
- *Fault Isolation*: Finding the exact location of abnormality.
- *Fault Identification*: Determination of abnormality's effects.

Therefore we can conclude that *Fault Isolation* and *Fault Identification* is the important part of FDI while *Fault Detection* is an obvious necessity. Detection of fault initiates the FDI application and Isolation and identification processes can be accomplished in simultaneously or one another dependent on system requirements[16].

Finally, a FDI application performance can be characterized according to following specifications[28].

- *Sensitivity* : FDI can detect relatively small sized errors.
- *Reaction Speed*: Time delay between fault's occurrence and detection of fault.
- *Robustness*: The stability of FDI application against disturbance.

On the other hand, the isolation (diagnosis) performance of a FDI is highly dependent on the model that it is based on[17]. However, most technical systems does not require *Fault Identification* except a nuclear plant or a flight-critical avionic system of a commercial airliner.

2.4.2 FDI Models

Indeed, FDI applications can be divided into two major branch; model-free and model-based according to functions they run and the mathematical background[18]. Model-free applications are simple to design and implement while model-based applications require a intensive development process and careful maintenance. However, only *model-based* applications are able to handle very complicated systems such as Boeing 777's FDI[15].

2.4.2.1 Model-free Methods

These methods offer very simple solutions for FDI without having a mathematical model. They are applied in most systems due to their simplicity for non-critical systems. Many techniques can be applied from *Limit Checking* to *Logical Reasoning* because of Model-free FDI's flexibility[19].

For example, model-free FDI can be implemented by multiple sensors measuring the same variable. If one of the sensors give different value then the others, the malfunction can be obtained. Another application is identifying a danger limit and warning limit to a sensor's measurement and simply monitoring the difference between variable and limits[19].

2.4.2.2 Model-based Methods

Model-based methods are based on the analytical relation between the actual system and the predicted system. Basically, process of model-based FDI is to determine the difference between predicted system and observed system as “normal” or “fault”[12]. In model-based method, some assumptions should be done in order to establish the system to a good algorithm[20]:

- There is no fault in the system initially and the design is appropriate.
- All system malfunctions can happen due to only given faults.

There are two major techniques to ground the FDI model of a system. Designer has to choose with regarding to available knowledge about two offered techniques. One way to reach a root-cause is to use an abductive algorithm where the model is based on the fault assumptions. In this algorithm, model contains faults assumptions and searches for matches when a actual observation that is modeled to be an effect of a fault[17]. Consider boiling water, the heater is on but the water is not boiling. Database claim should be as follows: “The water is not boiling although heater is on”. Then the model must have the fault knowledge such as heater is out of gas or water is not pure. If there is no information, algorithm would give no result out of this progress.

To overcome *abductive algorithms*’s this problem, *consistency-based algorithms* are based on correct behaviour of the model[18]. Then consistency-based claim is: “if the heater is working and water is pure then water must boil”. If we observe that water is not boiling then we must take the negative of either “heater is working” nor “water is pure” assumption. Then, we can not anymore observe boiling water and conclude that heater or water has a problem[18]. These processes are actually the fault detection and diagnosis that we are logically sure water is not boiling and the reason is heater or water. Then, *Fault Tree Analysis* or any other technique can be employed to address the exact problem.

2.4.3 Fault Detection and Isolation in Practice

Presently, aircraft diagnosis generally aims to produce a health status for the maintenance purposes by collecting and analyzing large amount of data. However, the diagnosis can be very critical in emergency situations during the flight when multiple fault warnings are generated and immediate action is required for flight safety. Therefore, CMS should generate corrective actions or advise troubleshooting in order to assist flight crew in decision making.

2.4.3.1 Time Dimension

Obviously, practical systems are generally time-varying and have temporal behaviour. Time-variance refers to behaviour that components can have different types of faults over time and temporal behaviour refers to the phenomena that an effect of a fault happens after a time interval[21].

Time is a fundamental dimension in model-based diagnosis and should be taken into account as a primary design concern[21]. Many diagnostic approaches contains the structural or functional model of the system as the diagnostic observations (symptoms) are extracted in a single time point. That is to say, observations are done in a time sequence rather than a multiple extraction.

The assumptions and descriptions in previous parts are based on theoretical model-based diagnosis while practical systems deeply requires a time dimension approach in order to realize the situation in a real aircraft[21]. The important definitions for temporal diagnosis are given in following parts.

2.4.3.2 Time Varying Context

The diagnostic observations are considered as a rapid group of status information as “normal” or “faulty”. However, real application’s observations are done in different times and for different time intervals. This may require a system that can change the testing method according to changing time to take time dimension into account[23].

2.4.3.3 Temporal Behaviour

Another important real application consequence is that a faulty behaviour symptom can be identified after a time interval then its exact

occurrence time. Because, most of the fault effects occur after some time and for some time. That is to say, observations of symptoms should be adjusted according to component's nature of fault, not only the structure of component[16].

2.4.3.4 Time-Varying Behaviour

The most typical behaviour of a real system , rather than its theoretical assumption, is the time-varying behaviour which is considered as the most difficult challenge when applying to a practical system. The real world's components may have different type of fault according to changing time where actually all model considerations change[16].

Example.2.1. Temporal Behaviour in Low Oil Pressure[16]:

Low oil pressure warning in an aircraft can be generated due to two reasons; Oil loss (leakage) or oil consumption. The starting of low oil pressure warning should be at least 2 hours after the starting of oil consumption. Also, oil consumption should be at least 2 hours long to cause a low oil pressure. The formulation in LaTeR language [9](Equation 2.1).

$$\begin{aligned}
 & oil_loss(T_{ol}) \rightarrow low_oil_pressure(T_{lop}) \\
 & Cons: \{T_{ol} \geq T_{lop}\} \\
 & oil_consumption(T_{oc}) \rightarrow low_oil_pressure(T_{lop}) \\
 & Cons: \{T_{oc} \geq T_{lop}, T_{oc} > 2, T_{oc} - T_{lop} \geq 2\}
 \end{aligned} \tag{2.1}$$

Consequently, temporal analysis can conclude following;

- If T_{lop} is less than 2 hours, low oil pressure can not be due to oil consumption but might be due to oil loss.
- If T_{lop} is between 2 and 4 hours, low oil pressure might be due to either oil consumption or oil loss.
- If T_{lop} is more than 4 hours, low oil oil pressure is possibly due to oil consumption.

In temporal diagnosis, it is important to consider the necessities of storing model's current situation and using it when the effect of the fault is observed. This brings the need for large memory and dealing with large amount of data those need to be kept while waiting for the effect of the fault[21].

2.4.4 Multiple Faults

The previous approaches considered that only one fault can happen at a defined time interval. However, real systems (especially military aircrafts) may suffer from multiple faults. Multiple faults refer to the faults those are not related to each other but have effects on the system at the same time interval[22].

In a commercial airliner, it is not likely to have two unrelated faults at the same interval thanks to redundant systems. However, the military aircrafts, those may suffer from hard flying conditions (hard-landings, dust, over-speed etc...) might cause multiple faults and their CMS should respond/adapt the aircraft immediately.

Dealing with multiple faults require numerous number of tests (sensors) that would support the constraints to make a diagnosis. However, installing sensors would make the diagnostic system eventually more complex with the additional cost and weight added to aircraft. Therefore, statistical techniques are applied to reduce the number of fault possibilities those are needed to be tested[22]. Consequently, the diagnosis process would be more efficient by saving memory and speed.

Example.2.2. Multiple Faults[22]

The digital circuit in Fig.2.17. is consisted of gates which can have faults individually by a symptom that they are either stuck at zero condition or stuck at 1.. A signal fault would require 8 test since each gate's two inputs should be tested. However, a multiple fault situation requires $3^4 - 1 = 80$ tests.

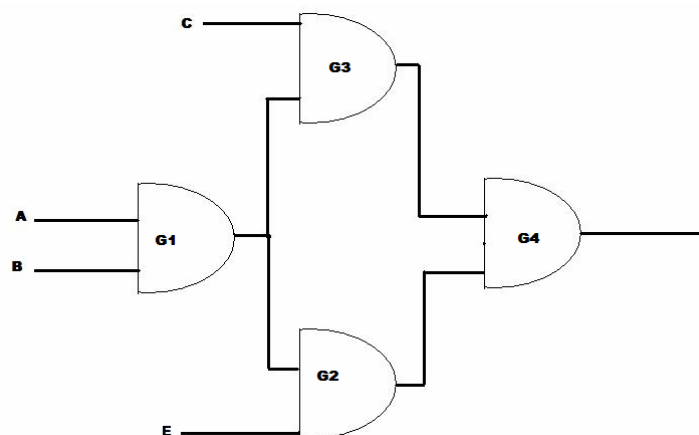


Fig.2.17. Digital circuit with multiple faults situation.

When the number of inputs to gates increase, the necessary number of tests are increased exponentially and this creates problem in the time and memory required for process[22]. A real application with thousand input would be obviously in efficient to apply for a diagnostic system. As it was mentioned, diagnostic systems employ statistical methods to reduce the number of possible test by eliminating the “less probable” tests[22].

2.4.5 Real-Time Diagnosis

In real-time diagnosis; when a fault occurs, the system should save the instant and adapt the model for new situation (faulty) and evaluate the next fault according to the new adapted model[23]. The human intervention should be considered according to task of the diagnosis. That is to say, the complexity of advisory information those needed to be presented to flight crew. System should rank the possible faults according to the diagnosis.

For example, Assume that the energy capacity of a battery varies with temperature and time. The battery’s capacity can be represented as a single parameter in battery model while a separate software component monitors the difference between the expected and observed battery voltage and modifies the battery cell capacity parameter to compensate for deviations[23]. Random changes should be ignored by the software and only the important changes due to temperature and time should be taken into account and adapt the new model.

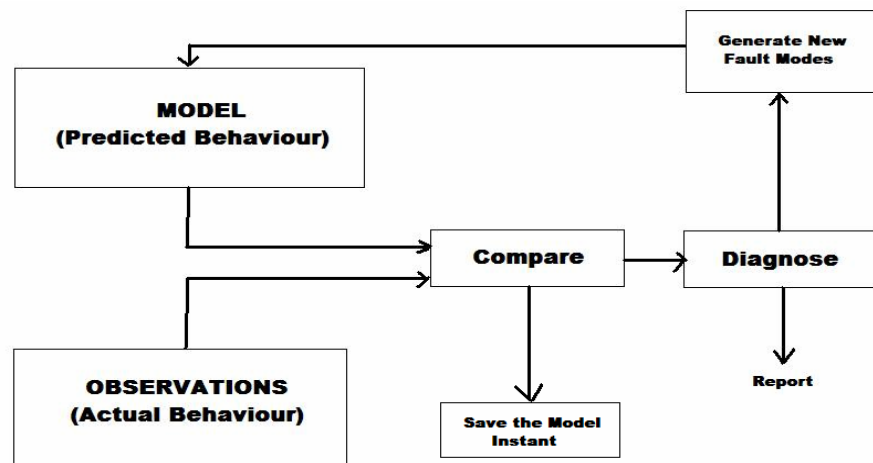


Fig.2.18. Real-time adaptation for model-based diagnosis.

When the modeled behaviour and the observed (actual) behaviour of a component are compared and a difference is identified, a fault diagnosis process starts. Before diagnosis, the complete state of the model is saved, and a separate temporary real-time model is instantiated in order to support fault diagnosis (See Fig.2.18)[23].

Once the fault is diagnosed as a specific failure mode of a specific element of the electrical power subsystem, the software component modeling that particular element changes its state to model the failure mode, and the overall real-time model is ready to detect another fault[23].

2.5 NATURE OF FAULTS AND TROUBLESHOOTING

This part provides a background to understand the nature of faults in commercial airlines and the approach of a human-based FDI which is basically done by aircraft maintenance technicians. A proper understanding about the faults are required to implement a FDI tool which is based on approach of a technician. The natural process of fault; *Entropy*, failure types according to their connections and troubleshooting are provided in order to form basis for intended FDI application.

2.5.1 Entropy

Every design has an expected performance and task according to the application which it works on. However, in the real application, the performance of the design is eventually smaller than what it was intended to. This phenomenon is called *entropy* and it constitutes a large theory in many engineering applications[30].

Obviously, every design's performance gradually decreases over the time by natural causes or due to extreme conditions. For example, if the design is made according to achieve a cheaper product, then entropy of the system increases. When the system is subjected to conditions which are over its operational limits, then the entropy of the system increases and a possible failure or unsatisfactory performance can be expected much more earlier as briefly illustrated in Fig.2.19. When we consider aircrafts, the following conditions increases the entropy[30]:

- **Environmental Deterioration:** Chemical interaction with environment.
- **Accidental Damage:** Human-sourced impacts and damages.
- **Fatigue Damage:** Due to long and/or stressful usage.

In order to keep the performance degradation minimum, as shown in Fig.2.19. aircrafts should be kept under a strict maintenance program which actually battles against the entropy.

2.5.2 Types of Failures

The possible failures in an aircraft can occur according to following scenarios which all needs a different type of maintenance approach. In order to implement a FDI, type nature of the fault should be classified according to following scenarios[29]:

- **Component Failure:** Standard failure with relatively simple solution. Problem is isolated from other components.
- **System and Environment:** Failure happens only in certain conditions e.g a components fails on flight but working on ground tests. It might require a intense inspection and testing.
- **Interaction of Systems:** Two related or unrelated systems cause a failure on each other e.g electromagnetic interference. A broader knowledge of systems and engineering might be required in order to solve the problem.

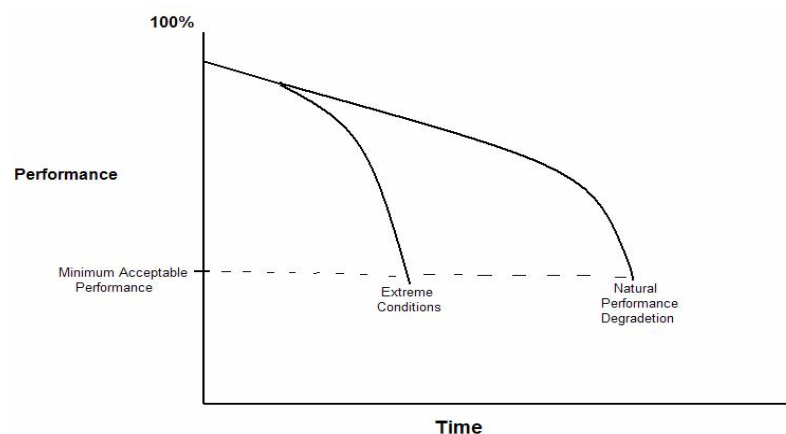


Fig.2.19. Performance degradation of designs[2].

In addition, the following type of failures exist due to design errors or improper maintenance troubleshooting[29,30]:

- **No Fault Found (NFF):** Whether there is actually no failure or it can not be found on the component. When NFF occurs, it is an indication of wrong maintenance approach.
- **Rogue Parts:** A specific series of a certain product has an inherit design error and fails continuously.
- **Bogus Parts:** When unauthorized parts are used which are produced by not the official producer.

2.5.3 Troubleshooting

In a simple description; solving a problem in aircraft requires a sequential approach by processing a logical troubleshooting. Applying a proper troubleshooting shortens the required time for repair and prevents unnecessary components removals. An example for a proper troubleshooting ,where the questions should be asked arbitrary, is given as follows[29,30]:

- **Problem History:** Previous failures to the same problem and the solutions which have worked before should be known.
- **Operation:** The configuration of the device should be tested if it properly turned on.
- **Cables:** The connection of cables to racks should be checked whether there is a blown fuse etc.
- **Multiple Systems:** The interrelated systems which effect each other's operation should be crosschecked.
- **Interfacing Systems:** The supporting systems should be checked whether they provide the intended power, hydraulic etc.
- **Enviroment:** The enviromental conditions should be checked whether they disturb the operation e.g temperature, humidity etc.

2.5.4 Maintenance Documentation

Processing a proper human-done *Fault Isolation* requires a intense documentation work whether while reporting the failure or executing a repair by following the maintenance manuals. There are numerous maintenance documents for each type of aircraft, even specific for aircraft operator such as components schematics, repair guides etc. However, two main documents constitute the outlines of maintenance; *Maintenance Review Board* (MRB), *Maintenance Planning Document* (MPD):

- MRB; This document is initially prepared for each type of aircraft regardless from its final operator. It contains the initial and minimum scheduled maintenance tasks.
- MPD; This document is based on MRB but contains the operator-specific tasks such as fatigue test, modifications etc.

Beside the numerous documents , which can be involved in FDI, a specific document provides the most of the knowledge support to the maintenance personnel. *Fault Isolation Manual* (FIM) contains the required logic queries and trees in order to find the root-cause of a problem.

3. INVESTIGATION AND ANALYSIS

In this part, the real-life applications of FID are described as the result of a field research in *Turkish Technic* maintenance company which was done in August 2010 as a part of “Investigation of Aircraft Technical Diagnostic Systems” research. During the field research; various other departments (rather than actual aircraft maintenance) are visited in order to investigate specific FDI tools for associated departments.

Especially, investigations in *Line Maintenance* and *Aircraft Maintenance* departments provided precious tips and informations about the possibilities to apply a FDI tool into aircraft maintenance (Part 3.1.5) and supported the outcome of *Field Research* (Part 3.2.2) which is actually the basic plan for the final work with the outcome of *Analytical Review* (Part 2) which was done during the Master’s Degree education.

Second part (3.2) contains the research’s intended FDI application for an example failure in *AC Power Generation System* of a Boeing 737-800 by using *abductive* and *consistency-based* approaches which are intended to combine with human-based FDI such as knowledge about the problem history (by statistical data) and troubleshooting approach as described in Part (2.5).

3.1 FIELD RESEARCH

Theoretical and investigative research contains background for aircraft computer systems, various reference approaches to computer centralized maintenance and underline the importance of FDI implementations in aircraft maintenance. In order to see the real applications and extract experienced information, a field research work was done in *Turkish Technic* company between August 03-07 August 2009.

Prior to field search, a work plan which is given in Table.3.1., was offered by the author and confirmed by the engineers in Turkish Technic. Certain modifications in work plan were done by company engineers in order to gain maximum efficiency for the intended research. Basically, the work plan intended to investigate the “real life” implementation and usage of *Central Maintenance System* (CMS) with additional information about general maintenance process in order to seek for areas where improvements can be necessary.

Briefly; field research started in *Engineering Directorate* where plans and long-term analysis of maintenance data are done in order to improve the efficiency of maintenance activities (See Part 3.1.3). A short intense course about general aircraft maintenance process was provided to the author in the associated engineering departments. Also, a short research about general avionic component failures and data buses were done in *Component Shops Directorate*. Afterwards, practical implementations of centralized maintenance techniques were investigated in *Aircraft Maintenance Directorate* where author gained precious information about various centralized maintenance programs of producer companies such as Boeing and Airbus (See Part 3.4.5). Finally, the onboard usage of CMC were investigated in *Line Maintenance Directorate* on Boeing 777-300, Boeing 737-800 and Airbus A 321 by monitoring the work of technicians and interviewing them about the usage of CMC (See Part 3.1.4).

This part starts with description of Turkish Technic company profile and capabilities which is followed by a more detailed report about the observations and investigations done in associated departments about the central maintenance. A conclusion which contains the outcome of the field research is given in the final part.

3.1.1 Turkish Technic Company Profile

Based at Istanbul's Atatürk Airport, Turkish Technic is the leading Aircraft Maintenance and Repair Organization in the region. Certified through EASA 145, JAA 145, FAA and Turkish DGCA for the performance of maintenance services, Turkish Technic offers a variety of maintenance services through its diversified shops, ranging from Airframe Heavy Maintenance, Engine-APU overhaul, LDG overhaul, etc.

The primary support is given to Turkish Airlines company which operates various types of aircrafts such as Boeing 777-300, Airbus A-340, Airbus A-330, Boeing 737-800, Airbus A-321, Airbus A-320, Airbus A-319. Therefore, the maintenance experience of the company is highly rich enough to provide intense information for the intended research of the Master's Degree thesis.

Table.3.1. Field Research Plan (03-07 August 2009, Turkish Technic Co.)

	Tuesday	Wednesday	Thursday	Friday
737-800 Technical Document Invg.	TC-JJC Boeing 777-300 “A” Check Avionic ADR Tests MAT Application	TC-JFN Boeing 737-800 “Transit” Check Avionic Tests Maintenance Check	FDI Tools Investigation Line Maintenance (737, 777, 330/340)	Boeing 777 (TC-JJC) Post-maintenance check
MMEL, MRB, MPD Document Invg. (737, 777)			Maintenance Computer Invg Line Maintenance (737, 777)	Training on Maintenance Engineering
Training on Maintenance Engineering			Interview with Technicians Aircraft Maintenance (737, 777)	“Emergency Plan” Maintenance Invg.
Flight Data Analysis Reliability (737, 777)			Safety Program Investigation	Field Research Evaluation and Presentation
Interview with Maintenance Engineers (737, 777)			Training on Maintenance Engineering	

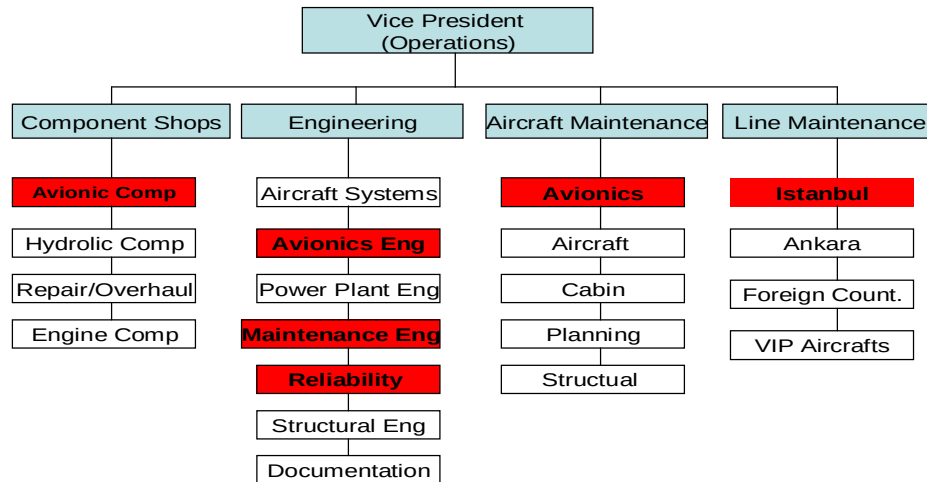


Fig.3.1. Organizational structure of technical departments in Turkish Technic where visited departments are coloured.

The organization of technical structure is given in Fig.3.1. where the field research was completed. The visited departments are coloured in the organizational department where it was seen necessary for the sake of Master's Degree thesis field research part.

3.1.2 FDI Process

The work plan in Table.3.1. and visited departments in Fig.3.1. helped to set the basic understanding of the maintenance in commercial aircrafts. The sequential visits to associated departments gave the opportunity to follow the process from its planning to line maintenance. Specially, field research was focused on utilization of *Flight Data Recorder* (FDR) cards, CMC status and the role of maintenance technicians on *Fault Identification and Isolation* (FDI).

Basically, field research intended to trace the data which is obtained by central maintenance (whether it is stored in FDR which is independent from the CMC). Therefore, the investigation which is described in following parts, the overall process of CMC status report (Termed as *Logs*) and flight data is briefly given as shown in Fig.3.2.

Line Maintenance acquires the CMC logs which presents the recorded failures during operation and removes the FDR cards for further analysis in required departments (Engines, Avionics, Structure etc.). *Reliability* department extracts from FDR cards the required flight data by other departments and puts them in order while *Aircraft*

Maintenance department evaluates the CMC logs in order to obtain a proper maintenance action. *Engineering* department evaluates the flight data, maintenance actions and aircraft producers' documents (Service Bulletin: SB) in order to improve maintenance plans. *Component Shops* makes the required maintenance action to LRUs and remove parts from aircraft.

3.1.3 Engineering Departments

Beside the practical maintenance action, a sophisticated maintenance planning is done in order to improve efficiency and safety. Therefore, the producer's maintenance documents and experiences from company's own maintenance actions are evaluated in *Engineering Departments*. Author intended to investigate any other utilized FDI tools which are used in "engineering" level.

3.1.3.1 Maintenance Engineering

This department applies the "maintenance science", which is briefly mentioned in Part 2, with regard to aircrafts official maintenance documentation in order to determine the

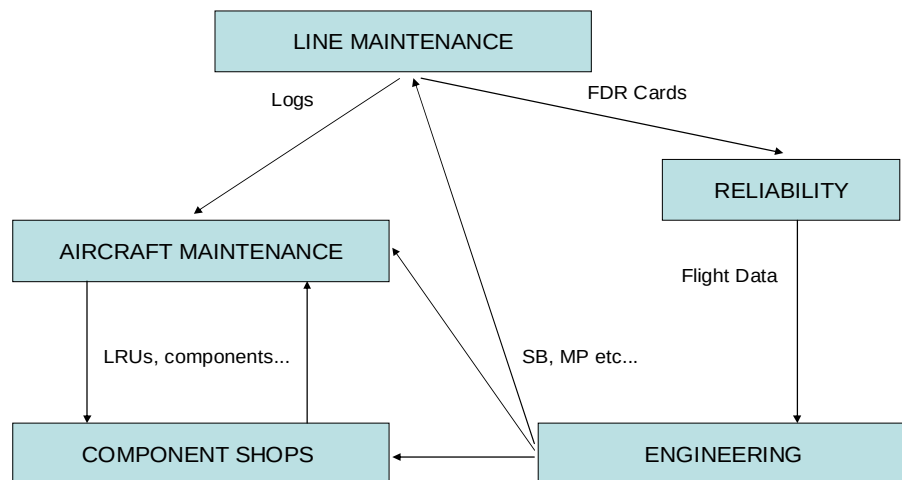


Fig.3.2. An overview for the maintenance process.

most proper maintenance program for the entire fleet. The *Maintenance Review Board* (MRB) document and *Aircraft Maintenance Manual* (AMM) of the aircraft producer are evaluated according to company requirements and the detailed maintenance actions in *Task Cards* such as maintenance interval, zone, access, descriptions are specified. This department prepares the *Maintenance Plans* (MP).

3.1.3.2 Reliability

The FDR cards contain a large spectrum of raw data which requires a special extraction. Reliability department gathers the FDR cards (whether they are SD or optic disc). Boeing uses SD cards which are more reliable while Airbus uses optic discs in order to store the flight data.

Especially, engine data are analyzed by a computer program, SAGE, in order to detect any potential failure by monitoring the performance degradetions. However, this is done in the associated *Power Plant Engineering* department. There is no any specific FDI tool in order to analyze avionic failures.

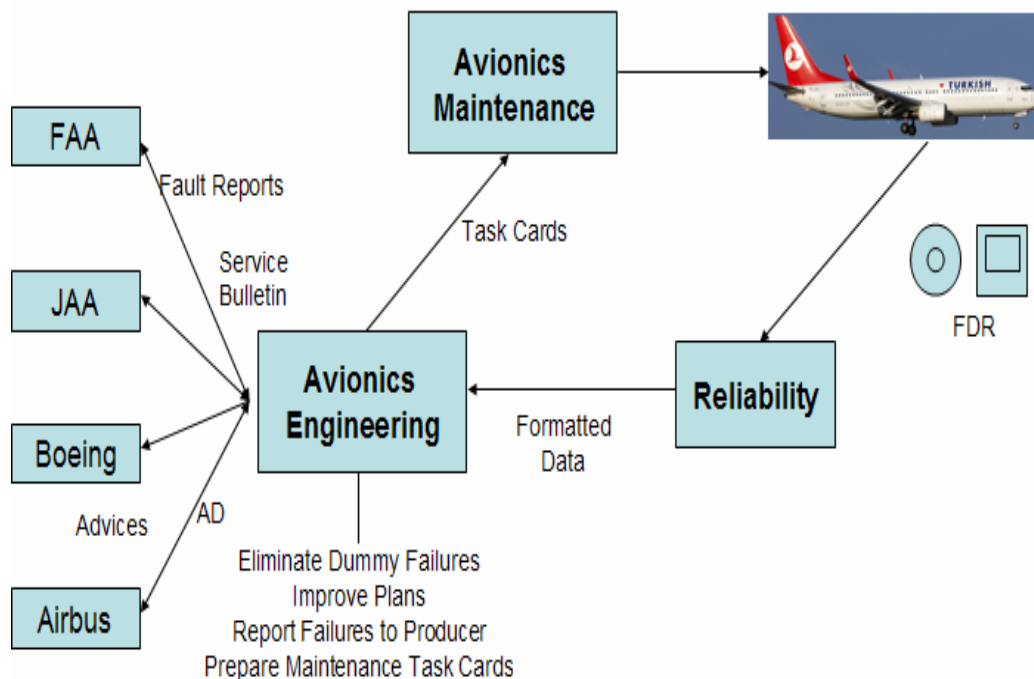


Fig.3.3. A brief description of maintenance loop for avionics.

3.1.3.3 Avionics Engineering

The fault history data from *Reliability Department* and maintenance logs from *Line Maintenance Department* are evaluated in order to eliminate dummy failures and renew maintenance procedure. The corrective maintenance documents from aircraft producers such as *Service Bulletin* (SB) or regulatory corrections such *Airworthiness Directive* (AD) are processed and conducted to *Aircraft Maintenance* and *Line Maintenance Department*. The “avionic maintenance loop” is briefly illustrated in Fig.3.3. This department utilizes various *Aircraft Health Management* (AHM) programs in order to keep the maintenance plan but there is no specific FDI tool in order to eliminate the dummy failures.

3.1.4 Centralized Maintenance

During the field research, Author intensively focused into *Avionics Maintenance* and *Line Maintenance* departments since they practically use the central maintenance computer (CMC) and utilize from various FDI tools. Author found the opportunity to observe technicians while they conduct a CMC check on Boeing 777-300 and Boeing 737-800 and also interviewed with maintenance engineers about the FDI’s usage in their specific systems.

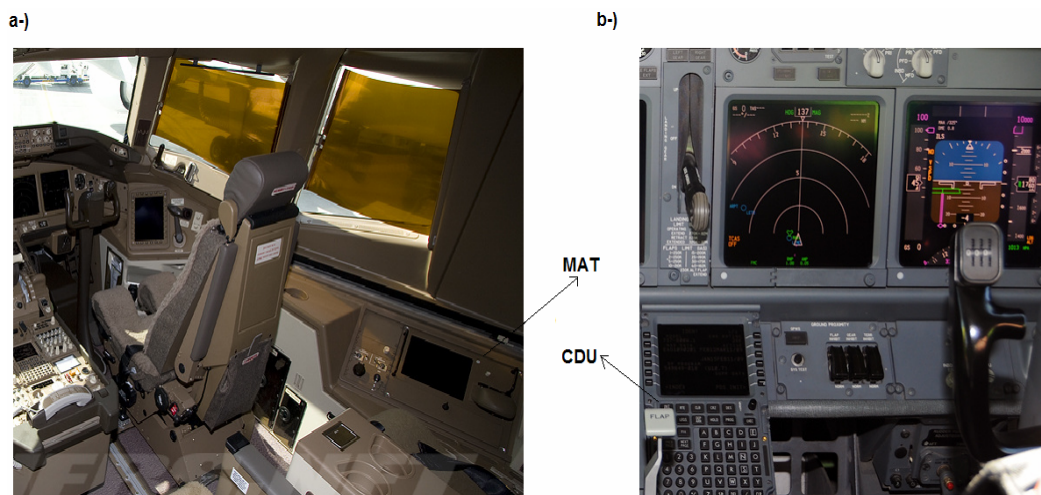


Fig.3.4. a-) Boeing 777-300’s maintenance access terminal (MAT). b-) Boeing 737-800’s MCDU where maintenance status is taken.

3.4.1.1 Maintenance Computers

The Boeing 777-300 has a sophisticated central maintenance system which is interacted by a separate *Maintenance Access Terminal* (MAT) which is located behind the pilot's seat as shown in Fig.3.4. On the other side Boeing 737-800 uses a specific CDU page which is called "Maintenance Page" in order to see the fault history recorded during the flight.

3.4.1.1 Boeing 777-300

During the periodic "A" check of a Boeing 777-300 (TC-JJC), a proper example for diagnostic was observed about the *Airplane Information and Management System* (AIMS) . Technicians checked the status in *Maintenance Access Terminal* (MAT) and read a failure in I/O Module 8 of the right AIMS. It was observed that CMC has pointed to pilots only the I/O Module 8 but not the systems which are connected to I/O Module 8 and eventually down. It also listed the systems which are failed because of the I/O Module 8. In addition, many other failure scenarios have been discussed with the technicians and engineers.

The failures are reported very detailed such as the phase of climb and suspected LRUs etc. Even more, some failures are not reported to flight crew during the flight but only presented to maintenance personnel in order to avoid confusion during flight. Associated failure is then found on *Fault Isolation Manual* (FIM) and proper fixing action is decided. A brief illustration for this process is given in Fig.3.5.

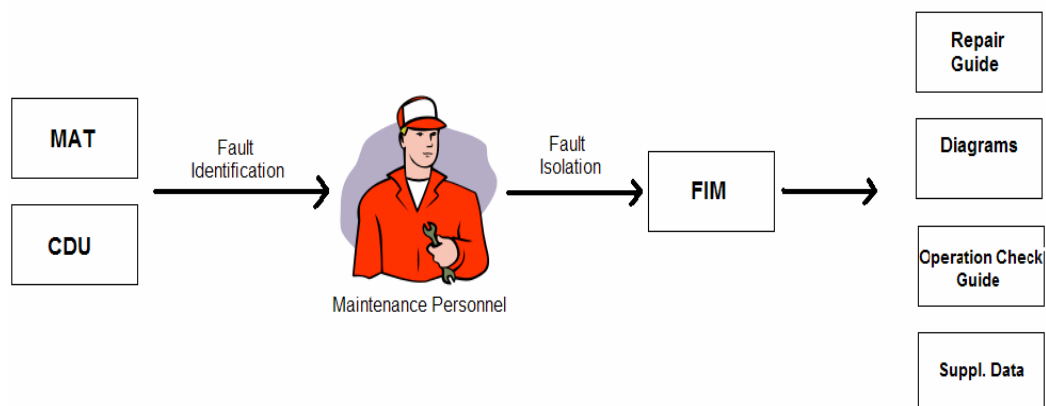


Fig.3.5. Maintenance action by using central maintenance computer diagnostic.

3.4.1.2 Boeing 737-800

During a “transit” check for a Boeing 737-800 (TC-JFN), a general interview was done with a technician while observing a maintenance check in *Control Display Unit* (CDU). A reported failure is given according to phase of flight and with “suspected LRU(s)”. However, different than Boeing 777-300, fault identification is relatively less detailed. For instance, a high number of ADIRU and related failures were reported in a failure investigation during the transit check. Furthermore, big portion of the FID process is done by the technician while he/she tries to “filter” the reported failures and determines which part of the FIM is required in order to approach to this failure.

3.1.4 FDI Tools

In Turkish Technic company, two FDI tools are utilized in Line Maintenance and Aircraft Maintenance departments for two different aircraft producer: *Airman* for Airbus and *myBoeingFleet.com* for Boeing aircraft. Screenshots for *myBoeingFleet.com*’s *Maintenance Performance Toolbox* feature is shown in Fig.3.6.

3.1.4.1 Airman

In addition to the reported failures and pilot’s logs, automatic failure messages are sent real-time to *Line Maintenance* where they are evaluated and fault isolation is started even before aircraft lands. There are two kind of failure messages: “Warnings” which pilots see and “Faults” which maintenance personnel see. Entire Airbus fleet is monitored whether they are grounded or airborne, with all their failure status and many other conditional information.

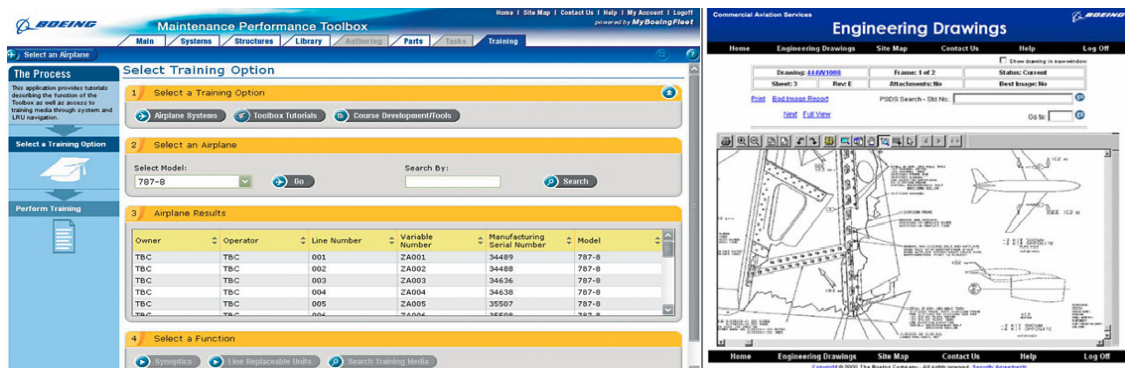


Fig.3.6. Screenshots of Boeing’s FDI tools.

Repair Solution Reference Number	Number of Reported Failures	Ratio of Successfull Repairs
7655-34-2-109C	56	48%

Fig.3.7. An example for Boeing’s FDI presentation for a certain reported failure

Airman receives the failure messages and presents a “Possible Causes” set according to its FDI. Afterwards, it initiates a “Troubleshooting” by asking observational information from maintenance personnel. The FDI is based mainly on FIM but also observational inputs, past failures, company’s failure history.

3.1.4.2 My Boeing Fleet

Boeing utilizes an internet portal where all Boeing operators around world can access and search for a solution for their reported failures. It also uses a similar approach to *Airman* to extract “possible causes” but it also present the information about other Boeing operators who had the same failure and the solution which they used. Fig.3.7. shows the an example for repair solution which is offered in Boeing’s FDI.

Even though, FDI tool makes the critical identification process, technicians still have to deal with a large number of maintenance documents in order to obtain the exact, required isolation solution.

3.2 PROPOSED FDI TECHNIQUE

According to the outcomes of literature analysis and practical observations in Turkish Technic Company field research, the following work is proposed as the final analysis of the Master’s Degree thesis.

This part primarily describes the approach and method of the proposed FDI technique which is based on the combination of literature review and practical analysis of the work. The sequential development description is followed by an demonstrative example for a Boeing 737-800 NG’s AC Electrical System failure where the avionic architecture is transformed to a logic tree and fault isolation query is done in the order of Troubleshooting (Part 2.5.3) and supported with failure intervals (MTBF, MTBCF).

It should be noted that the *Analytical Review* part is based on Boeing 777 type aircraft since it mostly utilizes from the central avionics approach. Due to complexity and lack of documentation, this analysis section is based on Boeing 737-800 NG aircraft where avionic components are relatively more convenient to study separately.

3.2.1 Work plan

The FIM document, where the failure modes and solutions are described, consists of logic trees for tracing the failure with a top-down or down-top approach by querying every node according to data and observations. Therefore, *consistency-based* diagnostic approach requires a tool for constructing logic structures of the operation and failure modes. As a result of a survey about logic programming tools, *Prolog* is obtained by covering most of the requirements for an aviation platform's logic structures.

3.2.1.1 Why Prolog ?

Prolog is a general purpose logic programming language associated with artificial intelligence and computational linguistics. *Prolog* is based on formal logic and it is declarative. The program logic is expressed in terms of relations, represented as facts and rules. Execution is triggered by running queries over these relations. Therefore, the interrelated and interacting architecture of aviation platforms can be expressed in terms of their relation by supporting them with the facts of sensor information, BITE etc. and rules which represent the fault scenarios. For example, the AC electrical system of Boeing 737-800[3] which is shown in Fig.3.8. can be transformed to a logic tree connections of *Prolog* as shown in Fig.3.9.

3.2.1.2 Method

The method for the proposed application of a FDI logic tool is given as follows.

- The required documents (Part 2.5) are gathered in order to obtain the list of components of a specific aircraft system to apply the FDI e.g electrical system.
- The logic tree of the chosen system is constructed in order to form the relations between components by referring to associated aircraft producer documents.

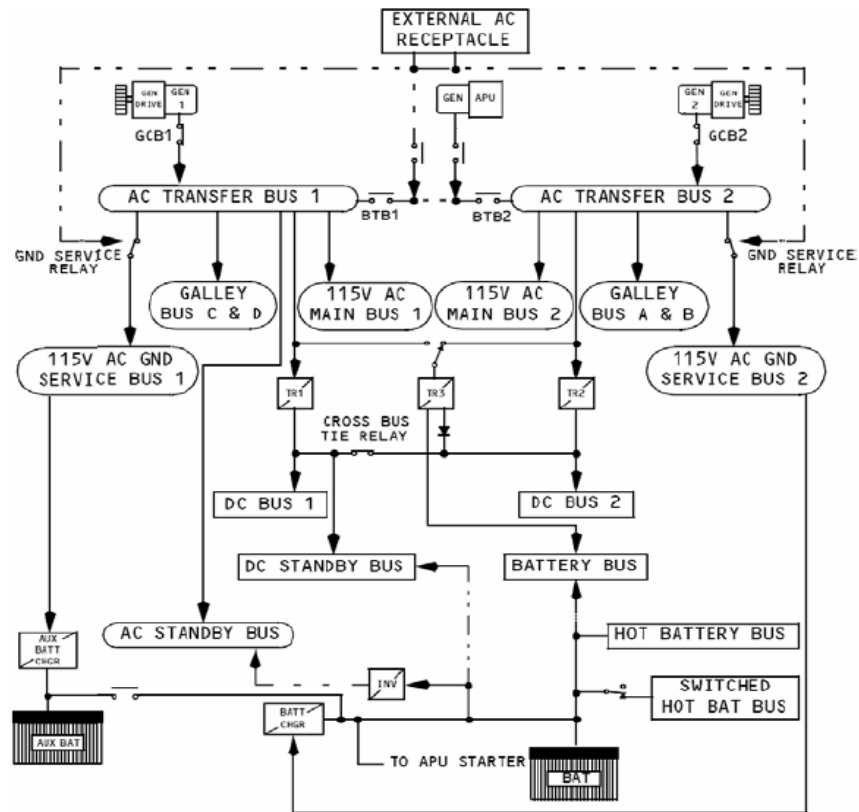


Fig.3.8. Flowchart of Boeing 737-800 Electrical System [3].

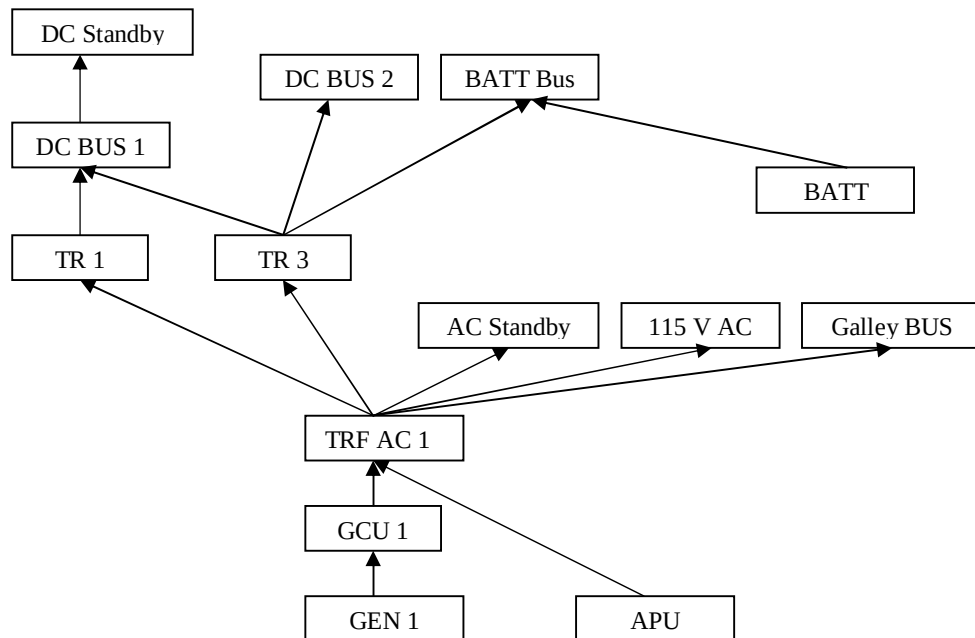


Fig.3.9. A prolog- convenient logic diagram for electrical system of Boeing 737 in Fig.3.8.

- The data (MTBF,MTBCF), which supports the *consistency-based* approach's exact fault location problem are gathered.
- Another classification about the “failure nature” (Part 2.5.2) is studied in order to seek for opportunity to apply different FDI algorithm with respect to the failure type.
- The logic structures can be implemented with *Prolog* algorithms and efficient *Fault Tree Analysis* methods are developed according to real maintenance *Troubleshooting* (Part 2.5.3) exercises.

3.2.1.3 Flowchart

According to Troubleshooting (Part 2.5.3), the fault isolation should ask the following in order; Component failure history, operation, wiring, interrelated components, interfacing components and finally the environmental effects.

“Failure history” query should contain the possible causes which were experienced before and the known time interval between two arbitrary failures which are recorded for the maintenance documentation. Therefore, the official failure reasons from Boeing's FIM document and optional user's inputs are taken and compared to determine if one of the failure reasons has significant higher *Mean Time Between Failures* (MTBF) value than others. In case of closed MTBF values; a second important parameter, Mean Time Between Critical Failures (MTBCF) is compared. The component with significantly higher MTBF or MTBCF difference gains a priority for the upcoming FDI process.

Second query is intended to distinguish if the possible failure reasons are interrelated or interfacing with the component. Interrelated components effect each other's operation in various ways and cause many unidentified problems since they perform operational data exchange. On the other hand, interfacing systems provide each other important sources such as power which would possibly cause an entire failure rather than a complex failure which is hard to diagnose. Therefore, interrelated components are given priority in further FDI than the interfacing systems.

The final query simply executes the Boeing official FIM procedures by depending on user's observational inputs. A possible ambiguity can be solved by using the previous “priority” values. The three stage of proposed FDI approach is given in Fig.3.10.

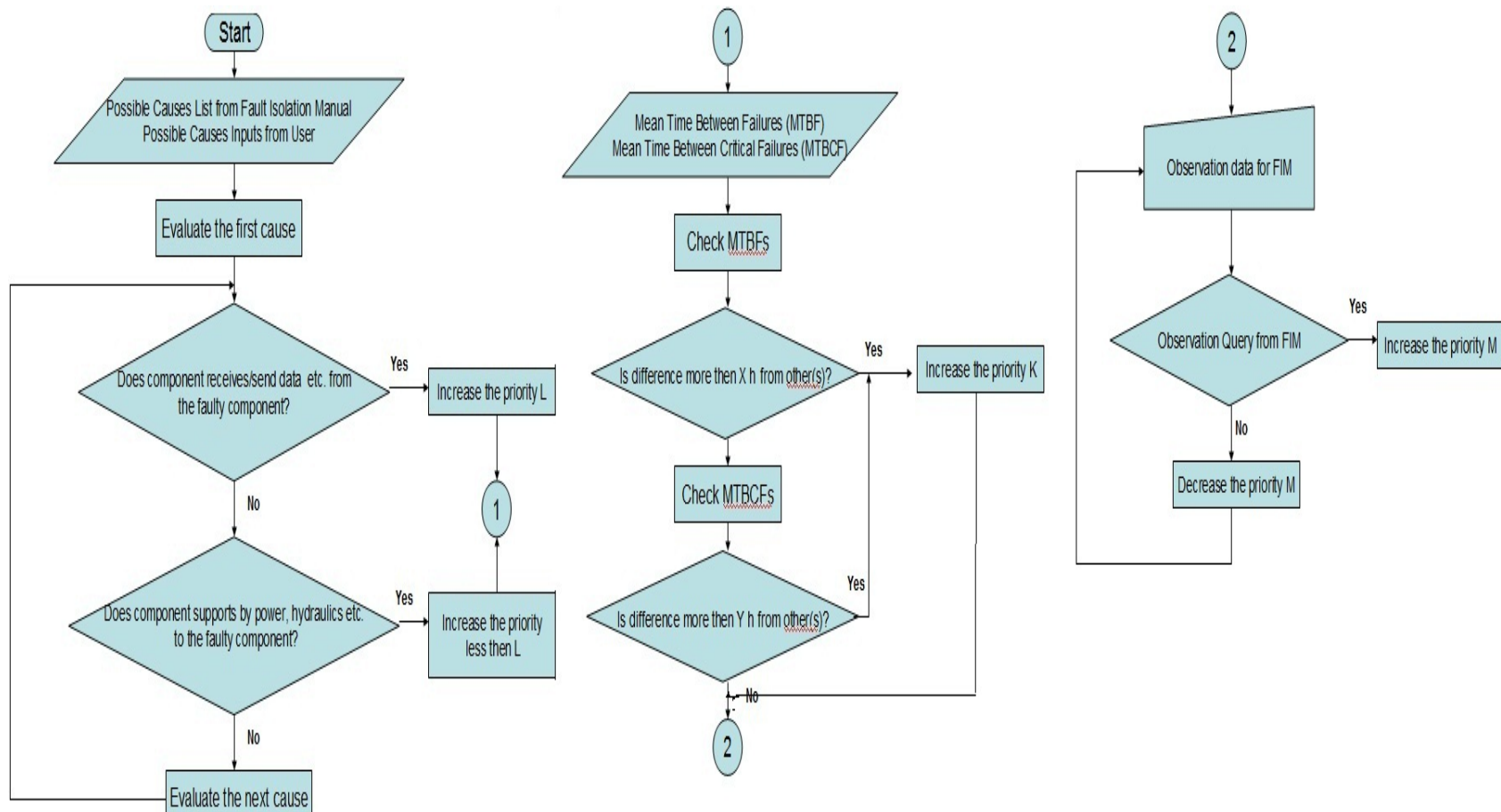


Fig.3.10. Flowcharts of the proposed approach for evaluating the priority in FDI.

The priority coefficients; K, L, M which are shown in Fig.3.10. have to be determined according to importance of particular query. For instance, an airline company might want to rely more on problem history (experience); then the MTBF priority value K should be increased. However, it appears to be more convenient to rely on human observation (M), then to fault history (K) and finally to component relation (L). Using more queries would potentially solve more ambiguities in the final FIM fault isolation.

3.2.2 Boeing 737-800 AC Electric System Review

Primary electrical power is supplied by two engine Integrated Drive Generators (IDGs) which supply three-phase, 115 V and 400 Hz alternating current. Each IDG is responsible for their own associated electrical buses and can by-pass the other IDG's electrical bus when one of the IDGs is inoperative. The generated AC current is then transformed to DC current by Transformer Rectifier Units (TRU) in order to be used by avionic components.

The general control and monitor of the AC Electrical System is done by *Generator Control Units* (GCU) which are located in each of the generators. GCU has direct interaction with numerous components which are listed in Table.3.2.

Table.3.2 The listed parts for AC Power system fault isolation.

GCU Interacting Components	Abbreviation
Generators	GEN
Integrated Drive Generators	IDG
AC System Generation and APU Module	SGM
IDG Power Feeders	IDG Feeders
Generator Control Breaker	GCB
Bus Tie Breaker	BTB
Differential Protection Current Transformer	DPCT
Tie Bus Power Feeders	TBPF
Rigid Bus Assembly	RBA
Power Distribution Panel	PDP

It is important to note the sequential flow in the AC power generation where the top-side components such as GCU and IDG have high effect on bottom-side components such as PDP or TBPF. Understanding of this effect is convenient to realize a possible fault propagation. For instance, a top-side component “GCU Fault” warning is possibly related to an internal or wiring malfunction when other components give no warning. On the other hand, a “DIST BUS Fault” (Distribution Bus) failure might have more than one error source and related components such as IDG Power Feeders, RBA 1, RBA 2, GCU etc. Next part considers this effect with the utilization of logic approach which is proposed in this Master’s Degree thesis.

3.2.3 Fault Isolation Analysis; AC Generation System

The AC power generation system of Boeing 737-800 NG has seven warning indicators which are listed in Table.3.3. according to their priority. The warning indicators are shown according to their priority e.g in case of a simultaneous GCU and BTB fault, the BITE reports show only the “GCU Fault” warning since it is more top-side than BTB Fault warning.

Table.3.3. AC Power Generation System BITE warning reports

BITE Warning Report	Brief Explanation
GCU Fault	Internal GCU, wiring or SGM interaction problem.
IDG Fault	IDG undervoltage, over/under frequency, shorted diode
GCB/APB Fault	GCB is not in commanded position
BTB Fault	BTB is not in commanded position
FEEDER Fault	IDG current above/under 5 A or frequency ahead/before 10ms
DIST/BUS Fault	Detection of overcurrent or unbalanced phase
GCU PASS	-

The following parts contain the logic approach to AC power generation failures by using the Troubleshooting basics and failure intervals which are embedded into *Fault Isolation Manual* (FIM) procedural troubleshooting. A top-side component failure (GCU) and a bottom-side component failure (Feeders) are analyzed and given according to proposed technique in order to demonstrate the fault isolation process.

3.2.3.2 GCU Fault

Generator Control Unit (GCU) failure is relatively easy compared to others since it has the most top-side component. GCU Fault is given in this part to show the sequential increase in the complexity of fault isolation.

GCU Fault message occurs when an internal operation, switching or wiring problem is detected. Since GCU is at the top, there is only one “interfacing system” (Note the 5th order in Troubleshooting in Part 2.5.3) *AC System Generator and APU module*. Therefore the possible causes in priority: GCU itself, wiring or AC System Generator and APU module since the troubleshooting order should be : history, operation, wiring, interrelated system. Flowchart for FDI approach is briefly given in Fig.3.11. BITE tests should be done again before starting to a fault isolation to avoid an intermittent fault.

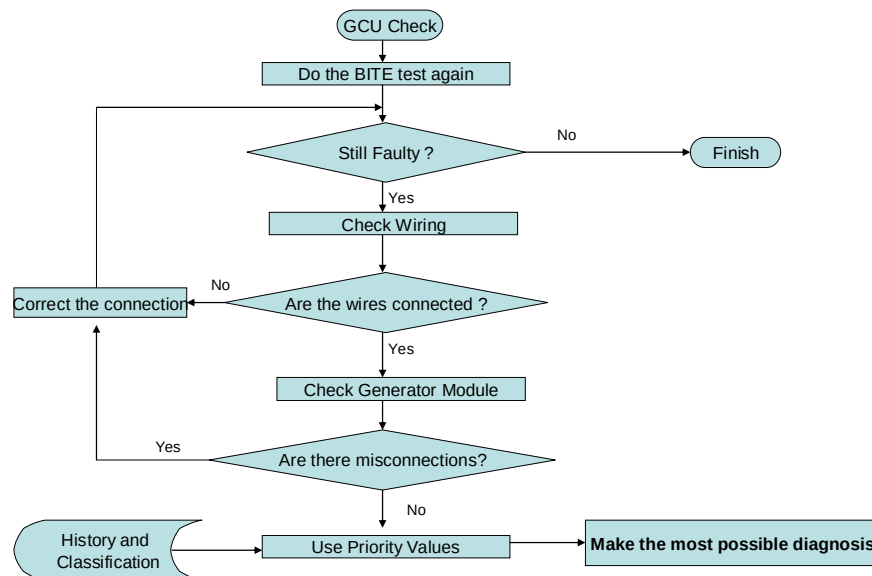


Fig.3.11. Fault diagnosis for a relatively simple scenario; GCU Fault.

3.2.3.4 Feeder Fault

This failure message occurs when there is a more complicated situation which involves various interrelating or interfacing components, observational and measurement inputs from the user. Feeder Fault is given when the current is 5 A below or above the normal +20 A current level. Also, a reversed phase sequence on the feeders causes this warning.

According to Boeing's FIM, the possible causes are; Integrated Drive Generator (IDG), IDG Power Feeders, Differential Protection Current Transformer (DPCT), GCU or wiring. Primarily, the distinguish between differential current or reversed phase should be done by the query; If Feeder fault is caused by reverse phase, generator will excite but GCB will not close and if the Feeder fault is caused by differential current, generator will not excite at all. Secondly, interrelated components (IDG, GCU) and interfacing components (DPCT, IDG Feeders) should be determined. Finally, FIM procedure should be executed by following the logic. All process is given in Fig.3.12.

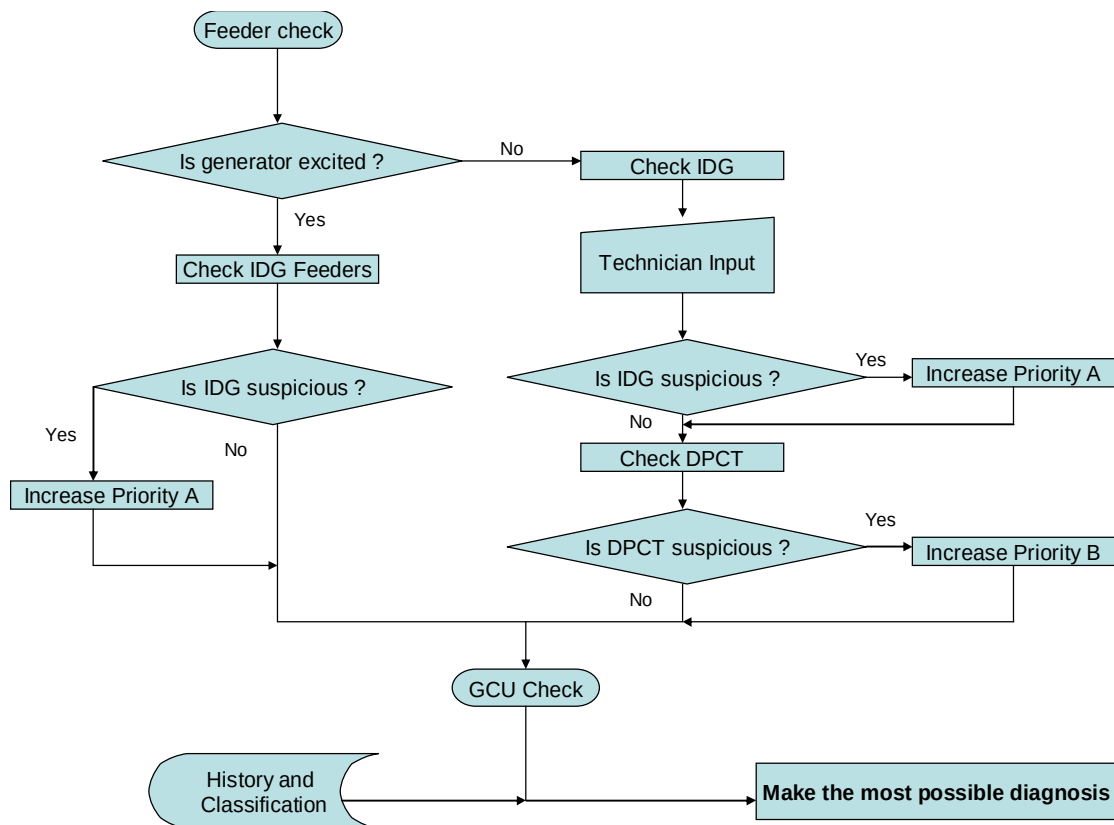


Fig.3.12. Fault isolation flowchart for Feeder fault in AC Power generation system.

4 RESULTS OF INVESTIGATION

This part contains the outcomes of theoretical and investigative research with the outcomes of field research. Since the Master's Degree thesis is a result of three *Research Works* which contain sequential flow of the general work, it is more convenient to present the results in same order as Research Work I, Research Work II and Research Work III (Field Research). In final section, the general results for all research is presented by counting in the proposed FDI technique.

4.1 OUTCOMES OF RESEARCH WORKS

Analytical Review part is intended to cover the all necessary literature search, necessary approaches and analysis for the sake of Master's Degree thesis. Therefore, a sequential work is presented which starts from basic central maintenance knowledge to specific information about the temporal behaviour in FDI. This part summarizes the outcomes of the research and concludes the intended work.

4.1.2 Summary of Computer Systems and FDI Methods

Research Work I is the primary literature search and provides the basic, necessary and comparative information about the computer systems of Boeing 777 and Airbus 330/340 aircraft. It also contains an introduction to *Central Maintenance Computers* and diagnostic approaches which are mainly used for aviation platforms. The outcome of *Research Work I* is the concept of *Fault Detection and Isolation* (FDI). It was seen that; in order to understand a failure logic in the system, the one should know the interaction of the components with each other. Finally, FDI approaches are discussed in order to get knowledge about algorithms for the intended work. *Abductive* and *Consistency-based* diagnostic approaches for FDI are evaluated as the most probable diagnostic approaches.

4.1.3 Summary of Architecture and Practical FDI

Research Work II is focused more on “architecture” of aviation computer systems which describes the interactions between systems. Knowing the interaction logic is

important in order to apply a proper FDI to the global system. Therefore, a basis about data buses is given since they provide connection between interacting systems. A special part is devoted to *Integrated Modular Avionics* (IMA) concept since Boeing 777 has an similar architecture. The nature of failures are intended to be understood in an IMA or close-to-IMA architecture.

Moreover, a realistic approach to diagnostic is given by discussing the *time-varying behaviour*, *time content*, *multiple faults* and *real-time process*. These properties are important in order to get knowledge about the difficulties when a FDI algorithm is intended to be applied. By gathering the a wide perspective about FDI, a field research was planned in *Turkish Technic* company in order to see real applications and decide the direction of research.

4.2 OUTCOME OF FIELD RESEARCH

Field Research (*Research Work III*) was intended to investigate any application which utilizes FDI in order to decide which application is more suitable for the final work. Various FDI applications have been investigated whether onboard the aircraft, in the maintenance hangar or in the engineering departments.

Engineering Departments evaluate the avionics failures which are reported by Line Maintenance and Aircraft Maintenance but none of the applications utilize a truly FDI algorithm except the engine diagnosis systems such as “SAGE”. Obviously, a *Aircraft Health Management* (AHM) application is utilized but it concerns about the general status of the aircraft rather than a specific failure’s isolation.

The real “Fault Isolation” is done in *Aircraft Maintenance* and *Line Maintenance* by mostly using the experienced technicians knowledge. Aircraft , surely, supports the FDI process by pointing suspected failures with its status report from *Central Maintenance Computer* but the precise isolation of the fault is still done by human work with utilizing various maintenance documents. The main assumed FDI document is the *Fault Isolation Manual* (FIM) where technicians follow various logic trees in order to locate the root-cause of the failure.

The aircraft producer programs such as *Airmen* and *myBoeingFleet* provide the primary FDI in *Line Maintenance* by evaluating the automatic or entered aircraft failure status in order to point suspected LRUs and even possible solutions for the problem. These programs utilize from various knowledge such as LRU’s theory of operation,

failure modes, operating modes and parameters such as *Mean Time Between Failures* (MTBF), *Mean Time Between Critical Failures* (MTBCF), *Mean Time Between Unit Replacement* (MTBUR). The FDI algorithms also use the history of similar failures, reports and successful solutions of other aircraft operators who had the similar failure.

4.3 RESULTS OF RESEARCH AND INVESTIGATION

The results of the Research Works about “Investigation of Aircraft Technical Diagnostic Systems” are articulated as follows:

- Avionics are highly interconnected and failures might be hard to locate.
- Central maintenance is required for proper fault detection where an overall failure evaluation can be done in order to achieve fault isolation.
- *Model-based diagnosis* is the proper approach to implement FDI.
- *Deductive* approach requires wide system knowledge and impractical to implement for the research. *Abductive* approach can be implemented since the failure modes are described in aircraft manuals.
- *Consistency-based* approach is more convenient with the support of data such as MTBF, failure history and failure modes.
- *Fault detection* is an onboard process by central maintenance computer while *fault isolation* is mostly done by human in maintenance hangar.
- Human-done fault isolation is based on central maintenance fault report but completed by referring to *Fault Isolation Manual* (FIM) troubleshooting manually.
- A *model-based, abductive* and *consistency-based* type approach which basically runs the FIM troubleshooting with the inputs of fault detection data of central maintenance computer can be implemented in order to make fault isolation with support of statistical data (MTBF, fault history etc.) and observation data from human.

5 CONCLUSIONS

As a result of analytical review of FDI and CMS:

- The onboard FDI algorithms are based on deductive or abductive model-based diagnosis since the aircraft producers have fully knowledge about the systems' operation. Also, onboard FDI algorithms are intended to detect and isolate the consequence of the failure without a deep analysis about the root-cause. When it comes to the hangar FDI on the ground; the system knowledge and observations are much more limited and the fault FDI should locate the failure's exact location. Therefore, consistency-based diagnosis is more convenient to apply in which the most probable failure cause is intended to be isolated.
- For future applications, FDI algorithms should take into account the proceeding *Integrated Modular Avionics* (IMA) architecture in which the avionics share common resources and located together. This revolutionary approach should modify the present FDI algorithms which are based on more federated avionic architecture.

As a result of investigation and analysis of FDI and CMS:

- The hangar FDI uses the failure reports of onboard maintenance computer and utilizes various FDI tools but human-based FDI is still the dominating method and its improper application may cause time waste. The hangar FDI tools should assist the hangar personnel in the decision of diagnose order which can prevent the technicians to start from a non-failed component. The main goal of a hangar FDI tool is to avoid unnecessary avionic removals from aircraft and shorten the maintenance down-time.
- Using failure history and component's types failure probability, the diagnose order can be adjusted according to priorities and maintenance personnel can determine the "most probable" avionic components to remove from airplane. Maintenance companies can apply their own statistical (MTBF, MTCF) and logical failure types (Rather than FIM) in order to modify their approach in a more specified form for their own company. Meanwhile, the companies can adjust the "priority" parameters whether they want to focus on failure history or they rely more on component's failure tendency.

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Appendix List

Appendix A. The Article presented for the Editorial Board of journal “Science – Future of Lithuania” 2010, vol.2.

Appendix B. The Article presented for the Editorial Board of journal “Science – Future of Lithuania” 2009, vol.2.

Appendix C. Certification of award for presentation in Aviation Technologies Conference 2010 held in Antanas Gustaitis Aviation Institute on 15 April 2010.



LOGIC APPROACH TO IMPROVE FAULT ISOLATION IN COMMERCIAL AIRPLANES' MAINTENANCE

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Abstract. This article presents a introductory knowledge about the Central Maintenance System and Fault Detection and Isolation process by a primarily onboard (aircraft) application background. Subsequently, hangar (on the ground) FDI process and its real requirements are discussed by presenting the overall „real“ fault isolation process of human. Finally, a proposal technique is given with its features which are intended to improve FDI and prevent unnecessary avionic removals from aircraft. Conclusions are pointing the necessary approach to apply proposed FDI technique.

Keywords: Fault Detection & Isolation, Model-Based Diagnosis, Central Maintenance System, No-Fault-Found, Expert Systems, Troubleshooting

Introduction

Airline operation is a huge coordinated work which involves many different individual members such as dispatch, flight operations, maintenance, cargo, catering, legal office etc. Among all these, maintenance has a particular importance since it has direct connection with the availability and sustainability of scheduled flights with strict time slots.

The unscheduled avionic maintenance, where an unexpected failure should be fixed rather than its periodic maintenance, has the 18% of all *Direct Maintenance Cost* (DMC) and about 40% of avionic equipment removals result as *No-Fault-Found* (NFF) after the inspection in maintenance hangar [Boeing Airplane Group, 1998].

The reason for unnecessary avionic equipment removals is the fact that modern avionic systems are highly interrelated and failures in the system are too complex to diagnose. It is essential to locate the root-cause of the failure by applying *Fault Detection and Isolation* (FDI) while many other interconnected subsystems may also give fault indications which may possibly hide the root-cause. Therefore, commercial airliners utilize *Central Maintenance Systems* (CMS) in order to diagnose faults by a more global perspective.

Presently, nearly all FDI approaches for engineering systems are based on *model-based diagnosis* after practical experiences in the past [Console, Dressier 1999]. According to completeness of the model, model-based diagnosis can be applied by using abductive,

deductive or consistency-based reasoning [Cheng, Ouyang 2003] [Peischl, Wotowa 2003]. Abductive approach requires the faulty model to interpret the best explanation or the most probable root-cause for a fault while consistency-based approach requires consistent observations and predictions [Poole 1989].

In practical avionics FDI; there is another front of fault isolation where the exact failure location should be found since CMS detects only the failure consequence but the “real fault isolation” is still needed to be done in the maintenance hangar.

The FDI process should start from the most possible cause of the problem by evaluating certain parameters to determine the order. The evaluating algorithm should contain experience data, official maintenance FDI and statistical information

This article presents a approach to avionics FDI and its practical issues. It discusses the real requirements and proposes a method to improve the commercial airliners' FDI by using a consistency-based logic approach which is based on human-based approach.

Problem; No-Fault-Found

When improper fault diagnostics is applied; the most undesired maintenance mistake, No-Fault-Found (NFF), increases the maintenance costs and decreases the dispatch reliability of the airline. It basically happens due to ineffective fault diagnosis while searching for the root-cause of the failure. NFF is the term when no failure is found in the avionic equipment after its removal from the

aircraft. NFF can happen due to two reasons; Firstly, the avionic equipment may actually not be faulty but an interrelated faulty equipment can cause its problem. Secondly, applied FDI tools or technicians are unable to locate the failure on the avionic equipment. NFF leads to longer maintenance down-times and causes delays for airliners. Fig.1 shows the big ratio of technical reasons in overall delay reasons. Therefore, an efficient FDI tool is critical to avoid unnecessary part removals in order to save time and money.

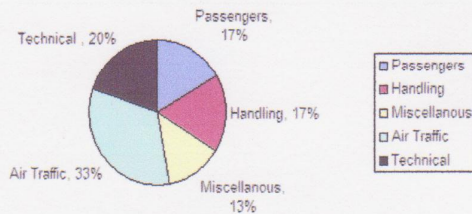


Fig. 1. Percentages of delay reasons in airline operation (ATA 2005).

Fault Detection, Isolation & Identification

Avionics have large number of interconnections which can let a single component's fault to propagate and cause other individual component's failure. Therefore, it is essential to analyze the fault reports to find the root-cause of the problem for a proper maintenance (less NFF). Certain terms in avionics diagnostics area are:

Fault Detection refers to the indication that something in the system is wrong (without showing the cause). **Fault Detection** is a must for practical engineering systems while locating the root-cause of a fault is called **Fault Isolation** and it is essential for diagnostic of the failure. **Fault Identification** (can be assumed as the „real fault isolation“ which is told in the introduction) refers to determine the exact location of the fault and it is necessary for taking a proper maintenance action. An example for a detection, isolation and identification sequence is given in (Fig. 2).

Fault Detection and Isolation (FDI) can be done by a widely-known logic approach, *Model-based Diagnosis*, which is widely accepted to be the best method for aviation platforms. Applying model-based diagnosis requires a global view to avionic systems which is provided by *Central Maintenance System (CMS)*.

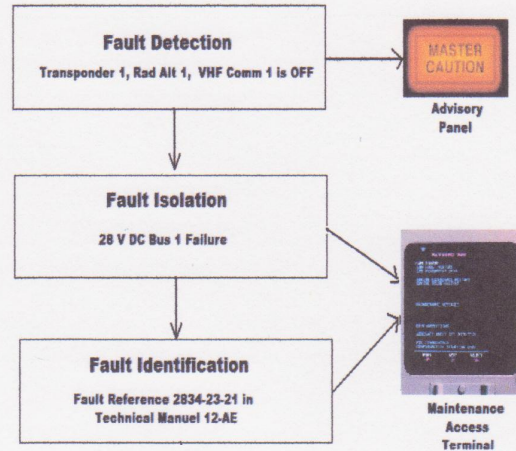


Fig. 2. Detection, isolation and identification for an assumed fault scenario.

Model-Based Diagnosis

Model-based Diagnosis compares the system's observed behaviour with the predicted model of the system. *Model-based* approach can contain the fault scenarios or the correct behaviour of the system which can be matched with the observations in order to conclude a diagnosis[Gertler, 1998].

It depends on the completeness of the system to define the predicted behaviour according to faulty or correct behaviour. When the model is completely known, *deductive reasoning* is used to detect consistent faults scenarios which are already defined. On the other hand, *consistency-based reasoning* can still extract the most probable faults or the best explanations for an undefined symptom when the model of the system is not completely defined.

Central Maintenance

Since the very early analog circuits, avionics have their *Built-in Test (BIT)* that continuously monitors their own system and has the capability to report a failure inside the system. The first CMS approach was only collecting BIT reports from individual avionics and presenting them in a central display to provide a general monitor for flight crews. As digital data buses were introduced, CMS started to receive continuous BIT reports and performed fault isolation (location) analysis to find out the root-cause among reported faults. New generation systems are expected to detect a fault before its occurrence (prognostic) and provide corrective action. Central maintenance system, as described in ARINC 624 standard, is simply illustrated in (Fig. 3).

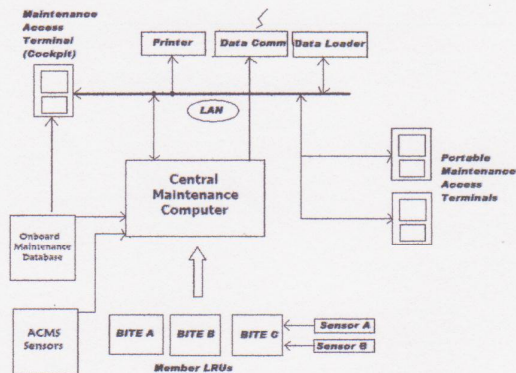


Fig.3. Central Maintenance System overview.

Central maintenance computer receives BIT reports and *Airplane Condition Management System* (ACMS) sensors' data to process them with regard to its diagnostic database. The status of the aircraft can be seen by *Maintenance Access Terminal* (MAT) screens in cockpit or by portable MATs of technicians.

The basic tasks expected from a CMS are as follows:

- Identifying the root-cause of the problem by tracing back the observed effects.
- Preventing the problem to cause another function to fail.
- Generating advisory warnings to cockpit.
- Keeping the necessary fault history and maintenance data for further analyze.

FDI in Maintenance Hangar

The previous parts covers the application of onboard FDI. The fault isolation onboard the airplane is more intended to report the consequence while the fault isolation in maintenance hangar has a more detailed process.

The failures are reported by the CMS by using various interfaces such as *Maintenance Access Terminal* (MAT, for Boeing 777) or *Control Display Unit* (CDU, for Boeing 737 and Airbus 320) very detailed such as the phase of climb and a list of suspected LRUs to maintenance unit (Generally Line Maintenance). Also, some failures are not reported to flight crew during the flight but only presented to maintenance personnel in order to avoid confusion during flight. The failures are reported to a centralized FDI tool in various ways as shown in Fig.4 where reports are evaluated by engineer and sent for *Fault Identification* to technician. Also, statistical information about component's failure interval

(Mean-Time-Between-Failures [MTBF]) is evaluated to obtain the most probable cause. Failure is then found on *Fault Isolation Manual* (FIM) and other necessary documents for determining a proper repair as shown in Fig.5.

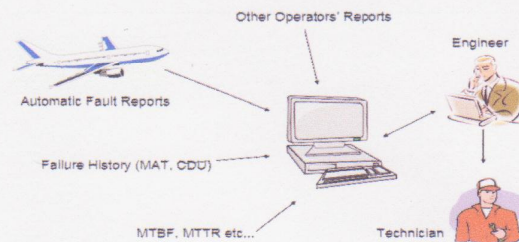


Fig. 4. An illustration for a proper centralized FDI process in maintenance hangar.

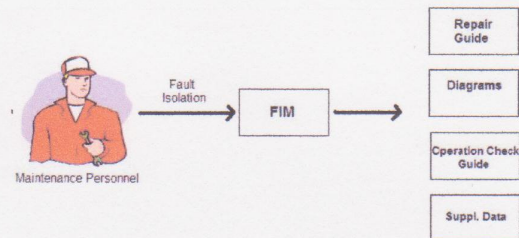


Fig. 5. The „real“ fault isolation process in maintenance hangar.

Types of Failures and Troubleshooting

The possible failures in an aircraft can occur according to following scenarios which all needs a different type of maintenance approach. In order to implement a FDI, type nature of the fault should be classified according to following scenarios[Kinnison, 2004]:

- **Component Failure:** Standard failure with relatively simple solution. Problem is isolated from other components.

- **System and Enviroment:** Failure happens only in certain conditions e.g a components fails on flight but working on ground tests. It might require a intense inspection and testing.

- **Interaction of Systems:** Two related or unrelated systems cause a failure on each other e.g electromagnetic interference. A broader knowledge of systems and engineering might be required in order to solve the problem.

In a simple description; solving a problem in aircraft requires a sequential approach by processing a logical troubleshooting. Applying a proper troubleshooting

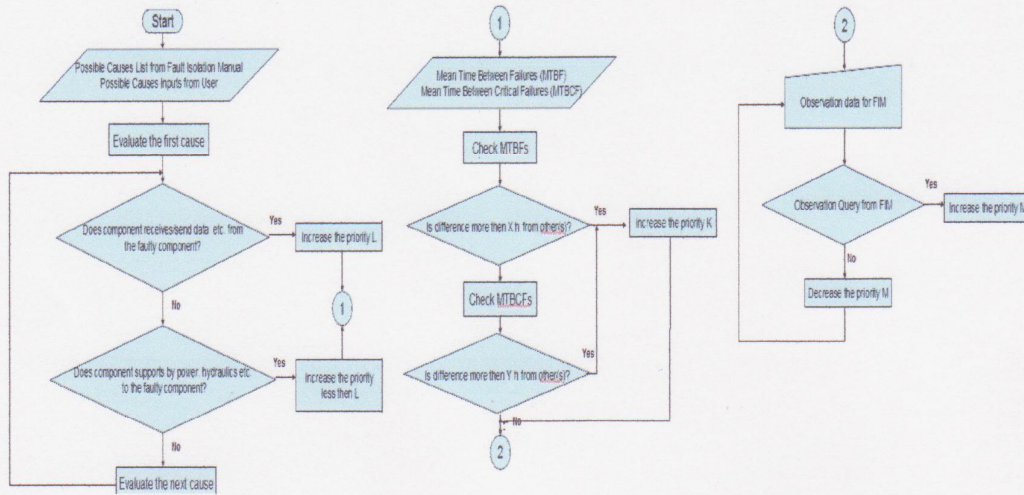


Fig.6. Flowcharts of the proposed approach for evaluating the priority in FDI

shortens the required time for repair and prevents unnecessary components removals. An example for a proper troubleshooting, where the questions should be asked arbitrary, is given as follows[Demirci, 2009]:

- **Problem History:** Previous failures to the same problem and the solutions which have worked before should be known.
- **Operation:** The configuration of the device should be tested if it properly turned on.
- **Cables:** The connection of cables to racks should be checked whether there is a blown fuse etc.
- **Multiple Systems:** The interrelated systems which effect each other's operation should be crosschecked.
- **Interfacing Systems:** The supporting systems should be checked whether they provide the intended power, hydraulic etc.
- **Environment:** The environmental conditions should be checked whether they disturb the operation e.g temperature, humidity etc.

Maintenance Hangar FDI Analysis

The key point in hangar FDI is to evaluate the possible causes efficiently and avoid NFF by starting to diagnose from the most probable component. The failure experience and the knowledge should be constructed in a logic approach by using the existing parameters and failure sequences. For instance, the statistical data of MTBF and MTCBF gives an important clue when we need to determine between two suspected components. Similarly, approaching to a failure by using the *Troubleshooting* basics where suspected components are classified according to their relation with the reported failure whether they are interrelated (data transfer) or interfacing (supporting).

In order to have failure sequences, existing maintenance documents such as *Fault Isolation Manual*

(FIM) is convenient to be constructed in a consistency-based (model-based) logic structure. Using consistency-based structure gives us the opportunity to determine the most probable cause even the observations are relatively small numbered.

Therefore, an algorithm which starts to diagnose with distinguishing about the components relation and comparing the statistical failure would change the priority of the suspected components in executing FDI. Fig.6 demonstrates the proposed algorithm which basically increases or decreases a „priority value“ before starting to ask questions about the consistency-based FDI.

The priority coefficients; K, L, M which are shown in Fig.3.10. have to be determined according to importance of particular query. For instance, an airline company might want to rely more on problem history (experience); then the MTBF priority value K should be increased. However, it appears to be more convenient to rely on human observation (M), then to fault history (K) and finally to component relation (L). Using more queries would potentially solve more ambiguities in the final FIM fault isolation.

Example Fault Analysis; Boeing 737-800 NG, AC Power System

The final phase, where the *Fault Isolation* is executed is demonstrated in following examples where *Generator Control Unit Fault* (GCU Warning) and *Feeder Fault* failures are evaluated according to proposed algorithm and diagnosed with a consistency-based approach.

GCU Fault message occurs when an internal operation, switching or wiring problem is detected. Since GCU is at the top, there is only one “interfacing system”, AC System Generator and APU module. Therefore the possible causes in priority: GCU itself, wiring or AC

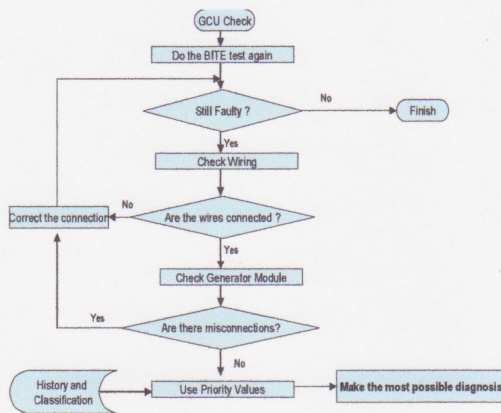


Fig. 6. Central maintenance system of Airbus A 330/340.

System Generator and APU module since the troubleshooting order should be: history, operation, wiring, interrelated system. Flowchart for FDI approach is given in Fig.7. BITE tests should be done again before starting to a fault isolation to avoid an intermittent fault.

GCU is on the top of logic structure of AC Power System and therefore has relatively easier fault isolation compared to a more down-side failure such as a Feeder Fault.

According to Boeing's FIM, the possible causes are; Integrated Drive Generator (IDG), IDG Power Feeders, Differential Protection Current Transformer (DPCT), GCU or wiring. Primarily, the distinguish between differential current or reversed phase should be done by the query; If Feeder fault is caused by reverse phase, generator will excite but GCB will not close and if the Feeder fault is caused by differential current, generator will not excite at all. Secondly, interrelated components (IDG, GCU) and interfacing components (DPCT, IDG Feeders) should be determined. Finally, FIM procedure should be executed by following the logic. All process is given in Fig.7.

Conclusions

- The onboard FDI algorithms are based on deductive or abductive model-based diagnosis since the aircraft producers have fully knowledge about the systems' operation. Also, onboard FDI algorithms are intended to detect and isolate the consequence of

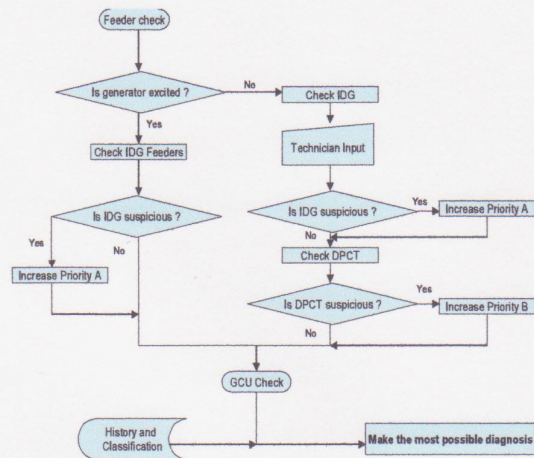


Fig. 7. Fault isolation flowchart for Feeder Fault in AC Power generation system.

the failure without a deep analysis about the root-cause. When it comes to the hangar FDI on the ground; the system knowledge and observations are much more limited and the fault FDI should locate the failure's exact location. Therefore, consistency-based diagnosis is more convenient to apply in which the most probable failure cause is intended to be isolated.

- The hangar FDI uses the failure reports of onboard maintenance computer and utilizes various FDI tools but human-based FDI is still the dominating method and its improper application may cause time waste. The hangar FDI tools should assist the hangar personnel in the decision of diagnose order which can prevent the technicians to start from a non-failed component. The main goal of a hangar FDI tool is to avoid unnecessary avionic removals from aircraft and shorten the maintenance downtime.
- Using failure history and component's types failure probability, the diagnose order can be adjusted according to priorities and maintenance personnel can determine the "most probable" avionic components to remove from airplane. Maintenance companies can apply their own statistical (MTBF, MTCF) and logical failure types (Rather than FIM) in order to modify their approach in a more specified form for their own company. Meanwhile, the companies can adjust the "priority" parameters whether they want to focus on failure history or they rely more on component's failure tendency.

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INVESTIGATION OF FAULT DETECTION AND ANALYSIS METHODS FOR CENTRAL MAINTENANCE SYSTEMS

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Abstract. Modern airplanes have a large number of interconnected avionic systems those need an accurate and confident real-time fault detection/isolation (FDI) monitor in central maintenance systems (CMS) for possible malfunctions or anomalies. The model-based diagnosis, which compares a predicted behaviour with the actual behaviour, are used for efficient analysis of maintenance data for FDI. This paper investigates the different type of model-based fault detection/isolation approaches according to different type of aircraft ideology. In addition, the importance of real-time (in-flight) diagnosis is discussed.

Keywords: Fault Detection & Isolation, Model-Based Diagnosis, Real-time Diagnosis, Central Maintenance System

Introduction

Having an overall look to aircraft systems or analyze of a system to locate a faulty component started to be very difficult as avionic systems became more complicated and interrelated between each other. This complexity increased the work load on flight crews and maintenance personnel on the diagnosis of a fault.

It is essential to locate the root-cause of the fault while many other interconnected subsystems may also give fault indications those may possibly hide the root-cause. Therefore, aircraft computers implement diagnosis approaches which collect data from sensors and computers to analyze them for a fault diagnosis.

Presently, nearly all diagnostic approaches for engineering systems are based on *model-based diagnosis* after practical experiences in the past [Console, Dressier 1999]. According to completeness of the model, model-based diagnosis can be applied by using abductive or deductive reasoning [Cheng, Ouyang 2003] [Peischl, Wotowa 2003]. Abductive approach requires the faulty model to interpret the best explanation or the most probable root-cause for a fault while deductive approach requires consistent observation and predictions [Poole 1989].

In real world's practical systems of aviation, the faults may have dynamic and time-varying behaviour [Console, 1997] that requires a proper approach to model

the aircraft for a good fault detection and isolation [Rahmani, Stone 1992].

Also, practical systems may suffer from the need of real-time diagnosis of multiple faults which is most likely can happen in an aircraft. Real-time diagnosis (in-flight) requires a model that adapts (changes) itself according to occurring faults and presents the most possible fault according to the new model [Jackson 1997]. Another practical experience, dealing with multiple faults, requires statistical methods that would reduce the number of components those are possibly faulty [Arjunan 1998].

In Boeing 777 airplane, the onboard diagnostics and maintenance system [Ramohalli 1992] collects the necessary data for FDI by applying a model-based diagnostic model and records for future process [Felke 1994].

The aircraft's avionic system architecture determines the diagnostic approach by constituting a centralized or distributed structure such as Boeing versus Airbus case.

Central Maintenance

Since the very early analog circuits, avionics have their *Built-in Test* (BIT) that continuously monitors their own system and has the capability to report a failure inside the system. The first CMS approach was only collecting BIT reports from individual avionics and presenting them in a central display to provide a general monitor for flight crews. As digital data buses were

introduced, CMS started to receive continuous BIT reports and performed fault isolation (location) analysis to find out the root-cause among reported faults. New generation systems are expected to detect a fault before its occurrence (prognostic) and provide corrective action. CMS, as described in ARINC 624 standard, is simply illustrated in (Fig. 1).

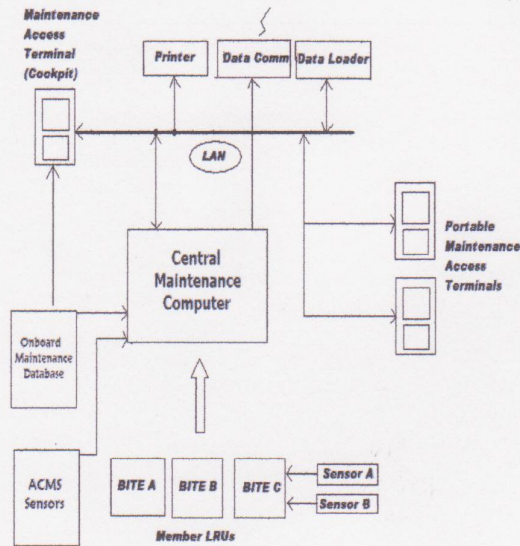


Fig. 1. Central maintenance system overview.

Central maintenance computer receives BIT reports and *Airplane Condition Management System* (ACMS) sensors' data to process them with regard to its diagnostic database. The status of the aircraft can be seen by *Maintenance Access Terminal* (MAT) screens in cockpit or by portable MATs of technicians.

The basic tasks expected from a CMS are as follows:

- Identifying the root-cause of the problem by tracing back the observed effects.
- Preventing the problem to cause another function to fail.
- Generating advisory warnings to cockpit.
- Keeping the necessary fault history and maintenance data for further analyze.

Fault Detection, Isolation & Identification

Avionics have large number of interconnections those can let a single component's fault to propagate and cause other individual component's failure. Therefore, it is essential to analyze the fault reports to find the root-cause of the problem for a proper corrective action or repair.

Fault Detection refers to the indication that something in the system is wrong (without showing the

cause). Fault detection is a must for practical engineering systems while locating the root-cause of a fault is called *Fault Isolation* and it is essential for diagnostic of practical systems. As a new approach, *Fault Identification* refers to determine the magnitude of the fault and it is necessary for taking a proper corrective action for the fault. An example for a detection, isolation and identification sequence is given in (Figure 2).

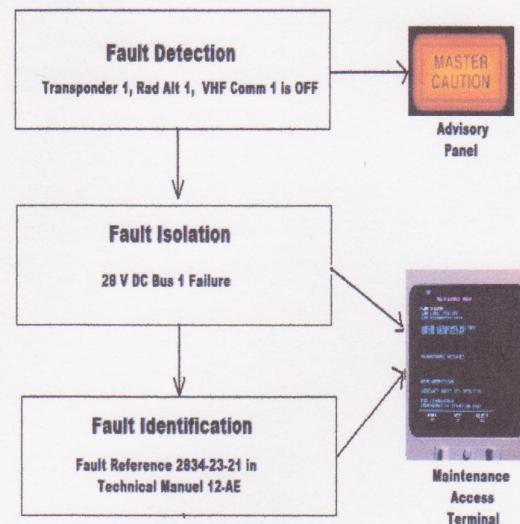


Fig. 2. Detection, isolation and identification for an assumed fault scenario.

FDI Methods

Model-free methods, such as *limit checking*, simply compare the observed value whether it exceeds the predefined limit or implement a special sensor that senses a individual diagnostic data. However, diagnosis of a complicated system (such as aircrafts) requires a more complicated technique [Gertler 1998].

Model-based Diagnosis compares the system's observed behaviour with a predefined mathematical model of the system. Model-based approach brings the advantage that it can contain the fault scenarios those can be matched with the observations in order to conclude a diagnosis.

Model-Based Diagnosis

In this approach, it is expected that system works correctly according to a predicted behaviour. If a fault is detected with regard to predefined set of correct behaviour or faulty behaviour, then a search for fault location is done with regard to predefined set of scenarios those can lead to the observed fault.

It depends on the completeness of the system to define the predicted behaviour according to faulty or

correct behaviour. When the model is completely known, *deductive reasoning* is used to detect consistent faults scenarios which are already defined. On the other hand, *abductive reasoning* can still extract the most probable faults or the best explanations for an undefined symptom when the model of the system is not completely defined.

Example 1. Deductive Reasoning:

It is absolute that the sum of internal angles of a triangle is 180° . This conclude that the third angle is 40° if the observations of other two angles are 80° and 60° . Considering (Fig. 3, a), the failure and effects can be easily defined for such a simplified system that only consists of a lamb and switch. Deductive approach constitutes that if both lamb and switch is ok, then there must be a light. Then the diagnosis can only be: If there is no light when the switch is ok, then either lamb or switch is faulty for sure. However, it can not evaluate other effects such as battery is low or cable is not conducting which are shown in (Fig. 3, b).

Example 2. Abductive Reasoning

Considering (Fig. 3, b), if there is a constraint such as battery has six hours of energy and we have sensor to measure it, a more probable diagnosis can be concluded: If the system clock is opened for 3 hours, then the battery can not be low and this leads to a diagnosis that cable might not conducting. However, it should be noted that this is only the best explanation rather than a certain diagnosis.

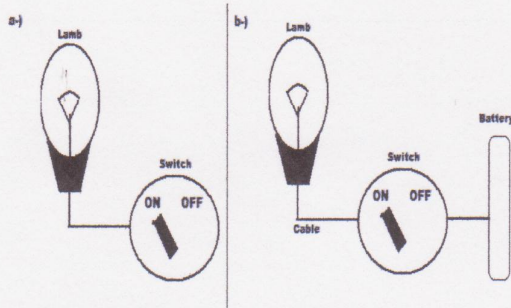


Fig. 3. Examples for a) deductive and b) abductive reasonings.

Temporal Diagnosis

Obviously, practical systems are generally time-varying and have temporal behaviour. *Time-variance* refers to behaviour that components can have different types of faults over time and *temporal behaviour* refers to the phenomena that an effect of a fault happens after a time interval.

Example 3. Low Oil Pressure[Console 1997]:

Low oil pressure warning in an aircraft can be generated due to two reasons; oil loss (leakage) or oil consumption. The starting of low oil pressure warning should be at least 2 hours after the starting of oil consumption. Also, oil consumption should be at least 2 hours long to cause a low oil pressure. The formulation in LaTeR language [Brusoni, Console 1997] is given in (1).

$$\begin{aligned} & oil_loss(T_{ol}) \rightarrow low_oil_pressure(T_{lop}) \\ & Cons: \{T_{ol} \geq T_{lop}\} \\ & oil_consumption(T_{oc}) \rightarrow low_oil_pressure(T_{lop}) \\ & Cons: \{T_{oc} \geq T_{lop}, T_{oc} > 2, T_{oc} - T_{lop} \geq 2\} \end{aligned} \quad (1)$$

Consequently, temporal analysis can conclude following diagnoses;

- If T_{lop} is less then 2 hours, low oil pressure can not be due to oil consumption but might be due to oil loss.
- If T_{lop} is between 2 and 4 hours, low oil pressure might be due to either oil consumption or oil loss.
- If T_{lop} is more then 4 hours, low oil oil pressure is possibly due to oil consumption.

In temporal diagnosis, it is important to consider the necessities of storing model's current situation and using it when the effect of the fault is observed. This brings the need for large memory and dealing with large amount of datas those need to be kept while waiting for the effect of the fault.

Multiple Faults

The previous approaches considered that only one fault can happen at a defined time interval. However, real systems (especially military aircrafts) may suffer from multiple faults. *Multiple faults* refer to the faults those are not related to each other but have effects on the system at the same time interval.

Dealing with multiple faults require numerous number of tests (sensors) that would support the constraints to make a diagnosis. Therefore, statistical techniques are applied to reduce the number of fault possibilities those are needed to be tested. Consequently, the diagnosis process would be more efficient by saving memory and speed.

In a commercial airliner, it is not likely to have two unrelated faults at the same interval thanks to redundant systems. However, the military aircrafts, those may suffer from hard flying conditions (hard-landings, dust, over-speed etc.) or anti-aircraft fire (Figure 4), might have

multiple faults and their CMS should respond/adapt the aircraft immediately.



Fig. 4. An A-10 military aircraft hit by numerous number of small-arms fire.

Real-Time Diagnosis

Presently, aircraft diagnosis generally aims to produce a health status for the maintenance purposes by collecting and analyzing large amount of data. However, the diagnosis can be very critical in emergency situations during the flight when multiple fault warnings are generated and immediate action is required for flight safety. Therefore, CMS should generate corrective actions or advise troubleshooting in order to assist flight crew in decision making.

In real-time model-based diagnosis; when a fault occurs, the system should save the instant and adapt the model for new situation (faulty) and evaluate the next fault according to the new adapted model. The human intervention should be considered according to task of the diagnosis. That is to say, the complexity of advisory information those needed to be presented to flight crew. System should rank the possible faults according to the diagnosis.

Dependence on Aircraft Ideology

Even though, both Boeing and Airbus produces aircrafts for almost same purposes with correspondent systems, their approach for aircraft structure differ. The main difference between Boeing and Airbus structures is the usage of data buses (Neglecting Airbus A 380 which uses centralized approach).

Boeing 777 uses centralized common multi-point ARINC 629 data buses which are named as Systems Buses (four), Flight Control Buses (three) and also some

number of point-to-point ARINC 429 data buses (Figure 5). Data collecting function is carried out by *Airplane Information and Management System (AIMS)* where all avionics share the same sources such as power supply, I/O ports, processors, common software etc...

In Airbus approach (Figure 6), systems are connected through point-to-point ARINC 429 data buses or/with some analog connections. This leads to that systems may have only single connection with each other. Also, data collection function is done by two *Central Maintenance Computers* themselves. Individual avionics have their own computerized components and sources.

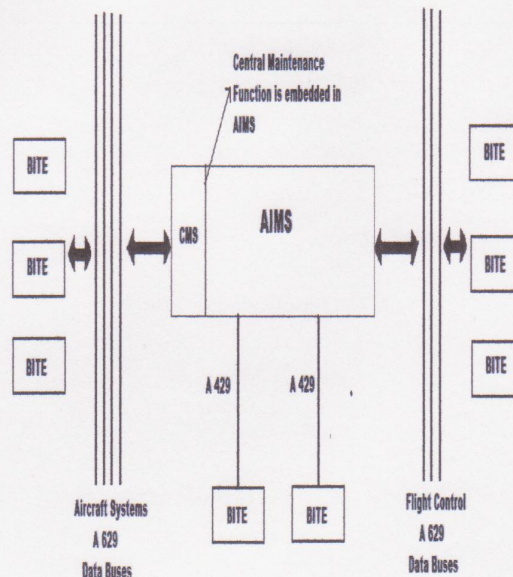


Fig. 5. Central maintenance system of Boeing 777.

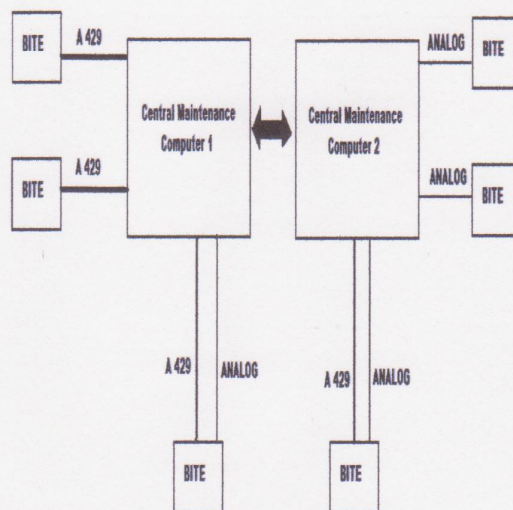


Fig. 6. Central maintenance system of Airbus A 330/340.

The centralized approach of Boeing's AIMS eventually makes it easier to detect a fault since the common sources of avionics are assembled together. Multi-point ARINC 629 data buses provide flexibility in re-directing (bypassing) faulty lines after fault detection. In Airbus's CMS, all avionics individually send their fault reports through a dedicated ARINC 429 line. This may increase the work load on FDI due to high amount of data from different sources and the possibility of misconnections.

Conclusions

1. Model-based diagnosis can work efficiently if the structure size of the system is modeled according to diagnosis task. A large model provides accuracy in diagnosis in maintenance thanks to many defined symptoms but this causes a slow speed in real-time diagnosis due to high number of symptoms those should be checked.

2. Temporal behaviour of faults should be considered carefully while modeling the system. A very dynamic model would be hard to design and maintain.

3. Occurance of multiple, unrelated faults is important to consider for military aircrafts' model-based diagnosis.

4. Aircraft's avionic system architecture (centralized or distributed) plays an important role on determining the diagnosis approach.

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This is to certify that *Cagdas Efe Balin*
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