Advantages of Systems Integration and new Technologies for Systems Testability Improvement during Aircraft Manufacturing Phase

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Abstract

Today's world requires achieving manufacturing objectives on time, on cost and on quality more than ever, which can only be achieved if manufacturing processes are considered and designed during product definition, being *collaborative engineering* the basis for the *design for manufacturing* and *design for testing* concepts.

Systems testing activities of large and medium aircraft (A/C) during manufacturing phase represent more than half of the complete production lead-time, which means that efforts for reducing testing times need to be made from the very beginning of the aircraft design phase. Current systems design, architectures and technologies allow the introduction of specific onboard functions for systems testability during A/C manufacturing phase, which leads to important reduction of testing time and improvement of overall testability activities.

This paper presents a global overview on current complexity to test A/C systems on ground during manufacturing phase and highlights the importance of defining and implementing specific onboard functions for these tests in the Final Assembly Line (FAL). The future should lead to standardisation on functions and capabilities, which could also be used for in-service maintenance.

1. Introduction

The manufacturing process of an A/C is a very complex process where multiple domains are involved, from assembly and components integration to systems installation and testing. In order to reduce manufacturing lead-time it is crucial to accurately study every single activity required during the whole process, determine how activities can optimally be integrated in the process and establish and plan the complete build process of the aircraft, which covers assemblies, mountings, fixings, riggings, and, for sure, systems testing.

Figure 1 depicts the manufacturing process of the Airbus A400M, which shows how the assembly and testing processes run from the reception of the A/C sections up to the delivery of the A/C to the customer.

From the assembly point of view, first, the main sections and components are received: main and nose fuselages, vertical and horizontal tail planes (VTP & HTP) and outer wings and centre wing box…)

Then, the first assemblies are carried out to build up the complete wing, the complete fuselage and the empennage.

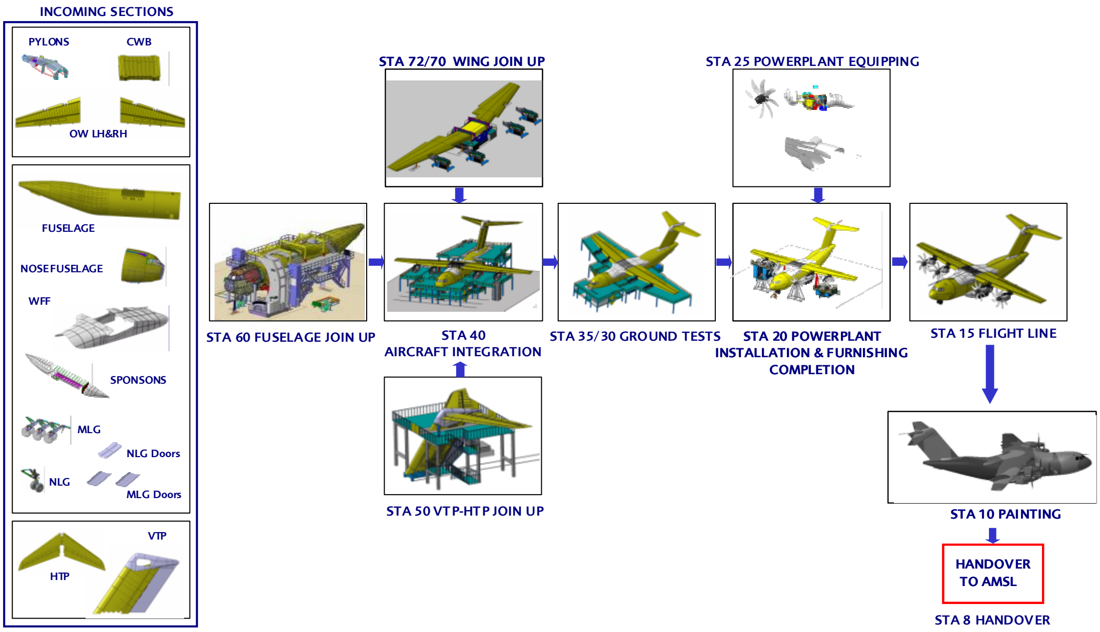

Figure 1. A400M Manufacturing Process.

In parallel, tests are carried out to test wing installations (mainly fuel-related installations), fuselage (electrical harnesses) and empennage (flight controls and hydraulic installations). But the most important testing phase starts once the main assembly of the A/C is finished and the electrical power-on is achieved as explained later.

Finally, these three main structures are joined up, resulting in a complete A/C structure. Other smaller structure parts are assembled later, being the engines the most important among them, which are mounted in a late stage in order to reduce store stock costs basically.

The electrical power-on of the A/C is considered one of the important milestones in the A/C manufacturing process. It implies starting up the electrical system of the A/C for the first time and checking that the electrical generation (partially) and distribution systems work correctly and are able to supply electrical power to the A/C systems. Once the A/C electrical power-on is completed the A/C is ready to face complete systems tests, which implies performing tests of different technologies such as electronics, hydraulic, mechanical and pneumatic.

A/C systems make use of the different technologies depending on the objective they are designed for and other considerations like technologies state of the art, architecture and equipment reuse from previous projects, COTS selection…

Examples of A/C systems are given hereafter to show how A/C systems have traditionally made use of the available technologies:

- Landing Gear: Mechanical/hydraulic
- Flight Controls: Mechanical/hydraulic
- Air Conditioning: Pneumatic
- Radionavigation: Electronics/antennas
- Fuel: Hydraulic/electronics

In the last years, thanks to the development of new technologies and architectures, important changes have deeply transformed A/C systems, being now possible the introduction of more and more functionalities with higher levels of integration. Along this paper some of these new capabilities shall be described and it will be highlighted how they can be used to improve A/C systems testability at FAL.

2. Collaborative engineering and design for testing

When designing a new A/C, top level functional requirements are first set. Once A/C performance and functionalities are clearly identified and defined, detailed design is launched in order to achieve functional objectives by specific design solutions that will be finally integrated and installed on A/C. This is a complex process that requires an enormous collaboration work between the different design teams to agree on solutions and get a common view on results once solutions are integrated.

Even more, manufacturing engineering that traditionally worked on defining industrial solutions for performing design final installation, integration and testing during the latest A/C design phase, requires nowadays the integration of specific requirements for industrialisation into the A/C design with the objective of better achieving industrial goals. The concurrent engineering methods and processes have been today changed into collaborative engineering, a concept that integrates design and manufacturing engineering and covers the complete product design and manufacturing processes definition from the very beginning of the project. In this way, processes that were defined in late stages of the project are now considered and designed during early stages, which allows feeding back and modifying, if necessary, the A/C design to better achieve industrial objectives.

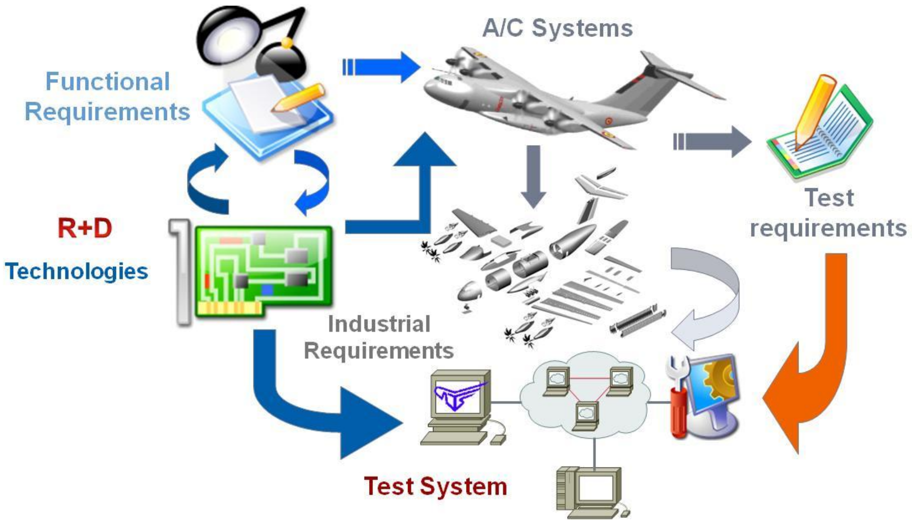

Figure 2. Design for Testing.

The collaborative engineering concept implies taking into account industrial objectives into early preliminary design phase in order to optimise results and objectives of industrial processes. In some cases, the collaborative engineering may lead to significantly different solutions from those where manufacturing engineering requirements are not considered, but in other cases, only small design changes with very little impact on design (and therefore cost), if considered in early design stages, may be necessary. This small design changes could imply important savings in terms of lead-time, recurrent and non recurrent costs linked to industrial means design, acquisition and maintenance, or even more, installation or integration feasibility.

The collaborative engineering concept applies also for ground tests to be carried out during A/C manufacturing. Whenever test requirements are considered in early design phases, if specific functions in A/C systems are designed and developed to better achieve these test requirements, important improvements can be obtained in terms of testing time and testing equipment needs, and therefore significant savings can be obtained during the A/C program life-time. Quality is also improved as far as less intrusive techniques are used to perform ground systems tests and more efficient and automatic processes can be put in place.

3. Ground Systems Tests

The objectives of the ground systems tests during A/C manufacturing are:

- the verification of the correct installation and final integration of A/C systems on board the A/C, regarding electrical, mechanical, hydraulics, pneumatics… installation after final mounting and connection.
- the acquisition and recording of the necessary measurements to demonstrate that the A/C meets its specifications and the certification authorities' regulations.
- whenever a new technical solution is embodied on A/C, the demonstration that the functional objectives of the new solution are met.

To achieve the previous objectives in an efficient and optimised way automation becomes mandatory. For that, during A/C design phase and as part of the collaborative engineering concept, it is of fundamental importance to identify the needs and requirements for designing, developing and integrating the automatic test system within the complete manufacturing process.

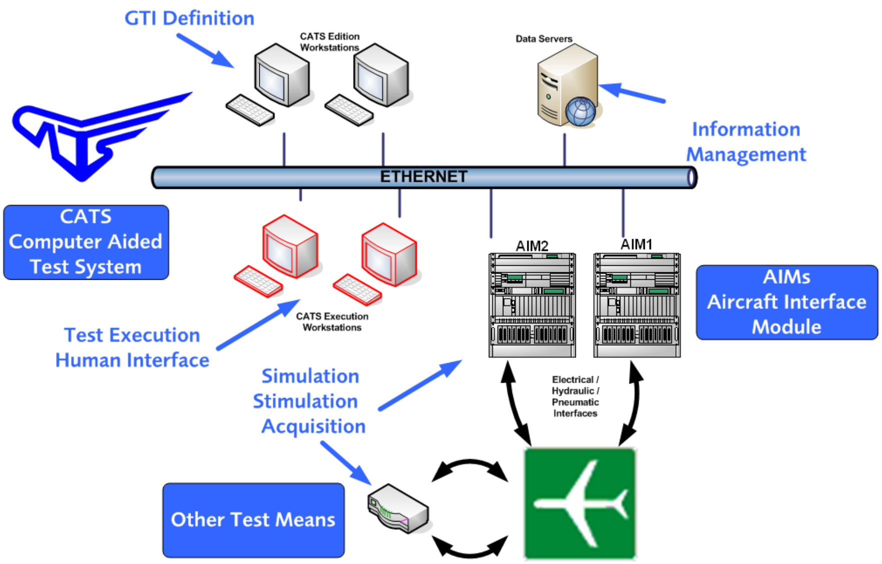

Figure 3. CATS® and AIMs Interfaces.

Airbus Military FAL ground test system is CATS® (Computer Aided Test System). CATS® is designed for the edition, execution, recording, analysis and management of Ground Test Instructions (GTIs) for Airbus Military programs. CATS® is composed of different modules that allow access to the multiple functionalities related to the whole GTIs aspects (edition, execution, recording, analysis and management) and the associated system functions (access, security, data recording and back-up…)

CATS® is connected to Aircraft Interface Modules (AIMs) in order to allow data exchange with A/C systems, subsystems or equipment under test. One AIM is a test equipment piece that, controlled by the Execution Module of CATS®, may replace an A/C piece of equipment, simulate an A/C interface, simulate A/C parameters, and/or acquire A/C parameters.

Most of the GTIs are executed making use of AIMs, which are usually (but not necessarily) controlled from the Execution Module of CATS® (there can be autonomous AIMs which can simulate A/C pieces of equipment and which are not connected to CATS®). The Execution Module is accessible from the Tests Execution Station, which is part of the Tests Execution Subsystem, and exchanges all the necessary information with the rest of the system through an Information Management Subsystem. The Information Management Subsystem communicates with other modules of CATS®, as the Edition Module, where the tests are prepared, or the Management Module, where the tests are scheduled, formalised and modified in terms of aircraft applicability. The Management Module and the Analysis Module are also used for the generation of all the required documentation for aircraft tests.

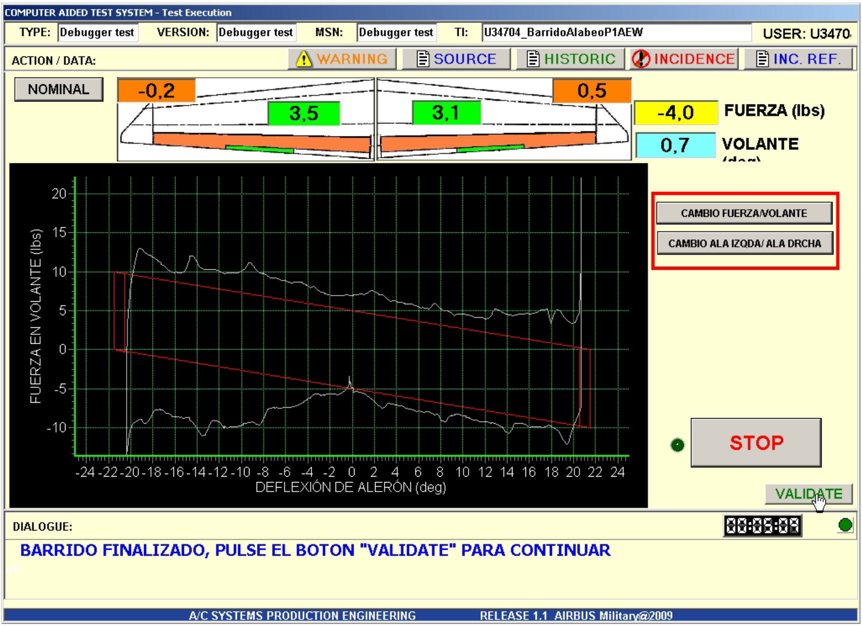

Figure 4. CATS® Graphical Interface.

The utilisation of an automatic test system for ground tests management contributes to improve manufacturing processes related to ground testability in terms of time, cost and quality. Indeed, if the appropriate functions are defined at A/C level, the improvement can be greatly increased.

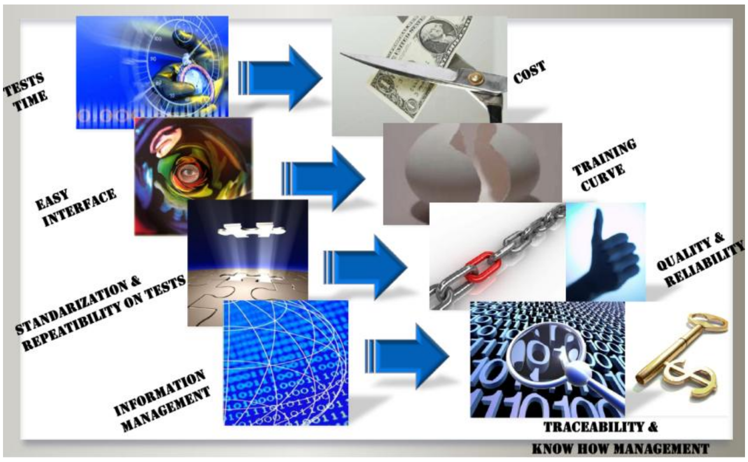

Figure 5. Ground Tests System Advantages.

The main objective of collaborative engineering regarding ground tests industrialisation is to define specific A/C accessibility and testability requirements to be taken account into A/C design. These requirements, once implemented on A/C will contribute to:

- reduce the need of test equipment (AIMs) by making use of the A/C itself as a means for generating and acquiring the necessary data for tests,
- reduce installation and removal time of test equipment, by providing easy access and specific connection points (electrical, hydraulic, pneumatic…) for test equipment.

The reduction of the number of test equipment to be used during ground tests and the improvement of access to connection points turn into benefits such us:

- reduction of test equipment development (non-recurrent) and maintenance (recurrent) cost,
- reduction of test time due to installation, connection and removal of test equipment,
- reduction of test time due to problems created by the test equipment themselves,
- improvement of systems testability and reduction of intrusive techniques for testing.

4. New technologies and architectures

The new technologies and systems architectures that have emerged during the last decades in information technologies (IT) and communications have produced a huge impact in the aeronautics industry. Some of the very well known standards used in automotive or IT products have been reused or adapted to be used in aeronautics products. In parallel, new designs and products have also been developed for the aeronautics industry thanks to the explosion of technologies and systems architectures.

This technological evolution has radically changed the way A/C on-board systems are designed and has permitted the development of new functionalities never used before. And all this, thanks to the increase of processing power in microprocessors, communications bandwidth between systems and integration level of last generation systems. New methodologies and development tools have also contributed to design and develop more and more complex systems, but also more powerful and versatile.

Examples of standards developed for non aeronautical products that have been used on board A/C systems are:

- the CAN (Controller Area Network) bus, that was first used on board the Airbus A380, but developed by Bosch during the 80's and used for the first time on a Mercedes-Benz in 1992,
- the AFDX (Avionics Full Duplex) network, used for the first time on board the Airbus A380, implemented based on Arinc 664 Part 7 specification, which is also based on the very well known IEEE 802.3 Ethernet standard designed in the 70's.

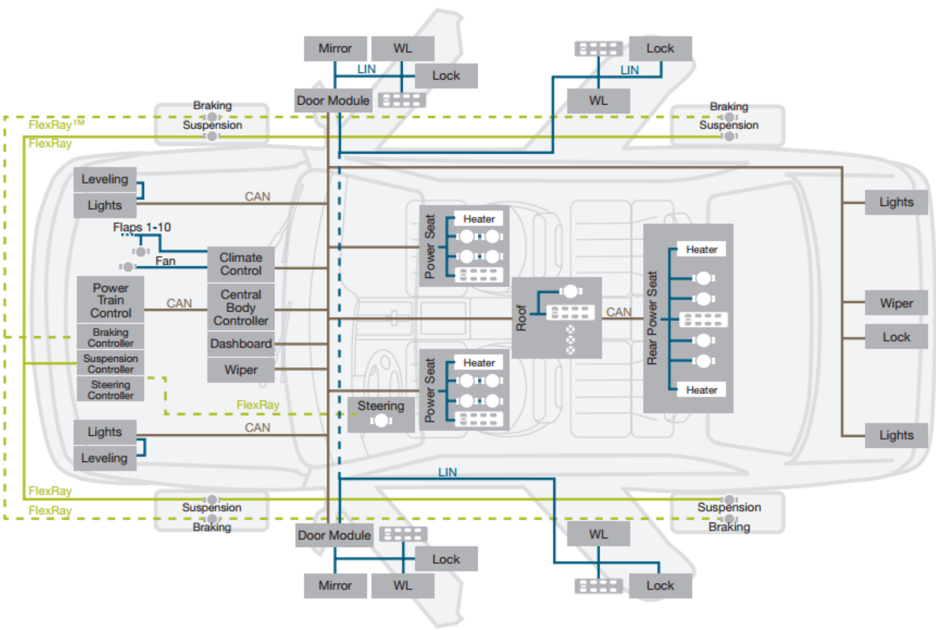

Figure 6. Automotive CAN Network Implementation [1].

During the 80's and 90's the systems development was mainly focused on creating more powerful and integrated electronics, with low power consumption. During the 90's the focus started to move from hardware to software, following personal computers' tendency. Today, no system can be conceived without a clear vision on its software development plan, being probably the most important part of the system as far as hardware tends to be considered a 'standard' platform capable of doing anything which depends only on software running on that platform.

On-board software has probably been the most important recent revolution in A/C systems. Some hundreds of software part numbers are now part of the configuration of the recent programs like A380, A400M or A350, whether only tens of them were previously managed in configuration by the A/C manufacturer. Software and hardware was managed by the equipment supplier, and once delivered to the A/C manufacturer the assembly of hardware and software became an equipment part number. The explosion of software development and management has simplified systems evolution, and has permitted the easy addition of new powerful functionalities, which can also be designed either for manufacturing or maintenance purposes. IMA architectures are strongly related to this software development explosion.

Three important evolutions have many things to do with new current systems architectures:

- First, the ability to interconnect easily any system with any other thanks to the use of communication networks like AFDX, with sufficient bandwidth to communicate a huge number of new functionalities.
- Second, the use of Integrated Modular Avionics (IMA) has contributed to the design of systems based on the development of integrated applications, being the software the brain of the system, and the hardware a more and more standard platform able to support any function.
- Third, the more electrical aircraft (MEA) concept, where traditional systems making use of pneumatic, fuel or hydraulic energy tend to be replaced by electrical energy.

Avionics Full Duplex

AFDX is based on the switched Ethernet technology to which specific services have been added in order to meet the requirements of avionics systems. These specific services are basically used to increase network availability and transform the network into a deterministic system. For that:

- the AFDX defines Virtual Links (VLs) with fixed routing, predefined bandwidth and BAG (Bandwidth Allocation Gap), and VLs monitoring function for bandwidth protection,
- the network is redundant with specific redundancy management mechanisms inside every network subscriber (End System).

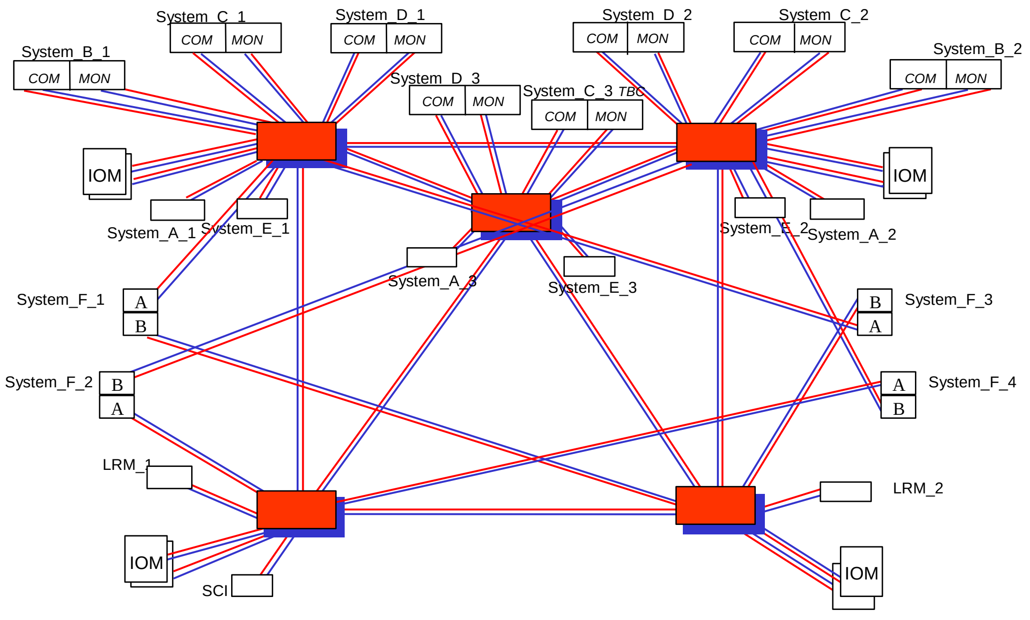

Figure 7. Example of AFDX Network Architecture.

Integrated Modular Avionics

IMA-1G architecture is being reviewed and is to be replaced by IMA-2G, under study and development thanks to the SCARLETT project (SCAlable & ReconfigurabLe Electronics PlatTforms and Tools), funded by the European Union within the Seventh Framework Programme (FP7).

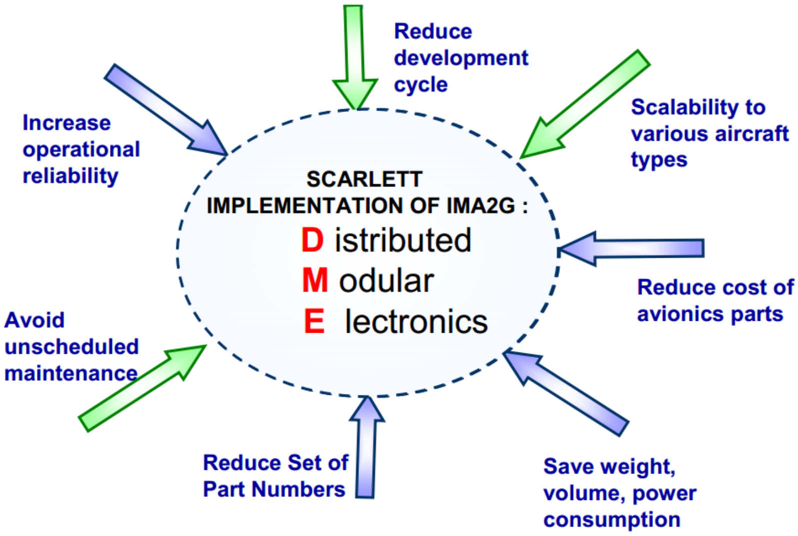

Figure 8. SCARLETT Project Objectives [2].

IMA-1G appeared as an answer to the increasing demands in terms of functions and performance in avionics systems installed on aircraft. The principle of IMA is to provide common or shared resources for computing and communication. This means that the computing functions of several systems may be installed in one common computing hardware platform (an IMA module) and use one common communication network for information exchange. IMA includes the following functions:

- partition management, including resources sharing between partitions,
- standard A653 Application Programming Interface (API) for applications programming access to module services,
- input/output management and conversion, including AFDX routing,
- inter-partition communication management inside the module.

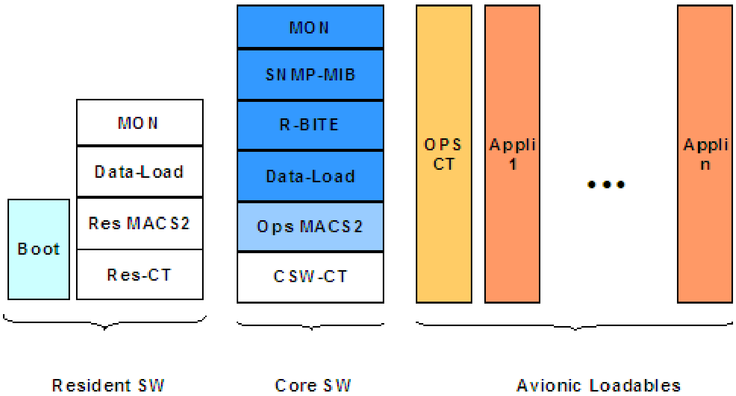

Figure 9. IMA Software Architecture.

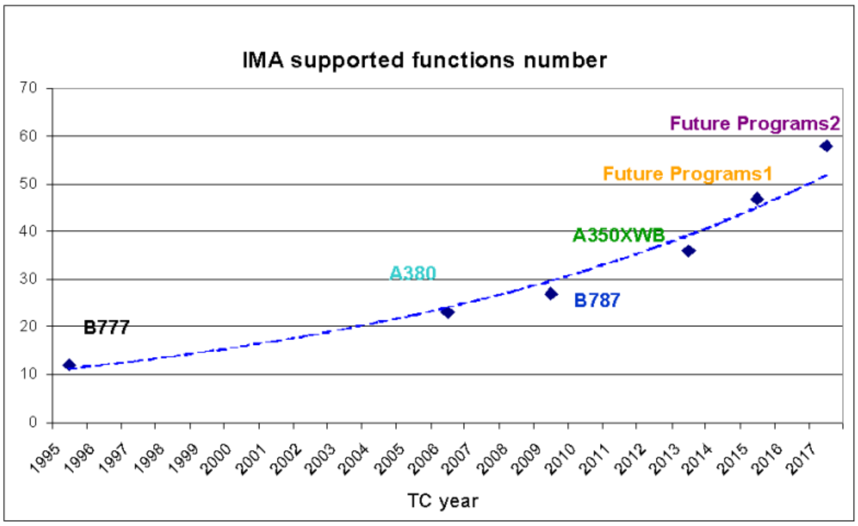

Figure 10. Evolution of IMA Functions [3].

It has to be highlighted that one important difference between IMA-1G and IMA-2G regarding systems architecture is the introduction of the distributed IMA concept, which implies that inputs acquisition and outputs generation is outsourced. The processing modules do not contain input/output capabilities any more, and input/output modules (Remote Data Concentrators) need to be developed and communicated with the processing modules.

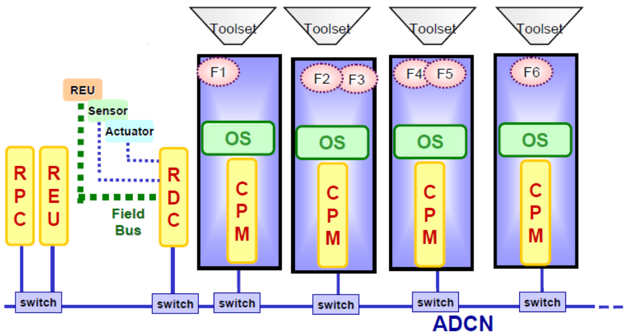

Figure 11. IMA-2G Architecture (DME) [4].

More Electrical Aircraft

The MEA concept permits design and more efficient operation of the A/C. Additionally, the technology improvement linked to the generation, storage and conversion of the different energies linked to the MEA concept will allow the reduction of fuel consumption with consequences on environment and operating costs.

Conventional A/C systems architectures use fuel to mainly produce propulsion power in engines (primary power), but also hydraulic, pneumatic and electrical power (secondary power) to feed A/C systems. The distribution of secondary power is carried out by complex networks that feed A/C systems with the requested redundancy according to safety requirements. The extraction and conversion of power from the engines to generate secondary power implies an important impact on engines design in terms of efficiency, weight and maintenance costs.

The main goal of the MEA concept is to avoid the use of hydraulic and pneumatic power on A/C systems and replace any of these by electrical power. Replacing hydraulic installations by electrical installations reduces A/C weight, simplifies complex pipes networks and avoids leakage risks of high corrosive fluids. Pneumatic systems are poorly efficient and present the difficulty to detect leakage, therefore their replacement by electrical systems also offers advantages. The disadvantages of electrical power are the low density of power compared to hydraulic systems and fire risk in case of short-circuit, but have a flexible non-complex architecture and easy integration in A/C.

The previous three analysed technologies and concepts (AFDX, IMA and MEA) have been and will still be in the near future key factors for the design of on-board A/C systems as can be observed in recent programs and in programs still in development or conception phase.

5. Advantages of Systems Integration and new Technologies for Systems Testability Improvement

From previous sections in this paper, it can be easily deduced that A/C systems architectures and technologies evolution do not only modify A/C functions and design, but also the test needs during A/C manufacturing in terms of tests to be performed and necessary test equipment. At the same time, A/C systems evolution allows the design of new functionalities specifically conceived for A/C systems testability on ground during manufacturing phase and the appearance of new technologies, systems and architectures that simplify testing activities. In some cases, functions designed for A/C maintenance purpose are also used during ground tests at FAL, which offers the advantage of reusing already designed functions for additional purposes.

The evolution of the technology and systems also contributes to improve the ground test system and test equipment, increasing processing power, adapting inputs and outputs capability management to new standards and offering more integrated solutions for tests generation, execution and management.

As already mentioned in section 2 of this paper, collaborative engineering in early design phases should integrate functional and industrial requirements into A/C systems design, which should lead to relevant on-ground testability improvements. But the collaborative engineering concept is not always easy to implement in an efficient way. The main difficulties are:

- During early design phases it is not necessarily easy to identify testability and accessibility requirements as far as systems design is not mature enough, but what’s even more important, installation definition may even not be started (it has to be in mind that the objective of most of the ground tests to be performed during manufacturing is to check the correct installation of systems).
- Once the design is mature enough, contracts are signed with systems and equipment suppliers. Considering the reduced development time and tight planning in new programs contracts are signed in many cases as soon as possible without considering testability and accessibility requirements. After contracts are signed it is quite difficult to add and/or modify requirements, with important associated costs difficult to understand by organisations, even when fully justified.
- Current organisations and work breakdown structures clearly identify different engineering teams for design, installation and manufacturing, which makes difficult to put them all together and make them work at the same time on common objectives. In many cases, the different teams work in areas geographically spread out.
- Design, installation and manufacturing engineering are deep and complex enough each other to allow the creation of engineering teams with the right knowledge on the three disciplines. Experience is crucial to have the right global vision in order to integrate all the necessary requirements.
- Adding non-functional requirements to the design is not always considered a benefit by design and installation engineers, who may not probably face the installation and testing problems during manufacturing phase. It is really important to make the whole organisation understand that common program objectives are more important than team or individual objectives, that collaborative engineering is the basis for optimised designs, and whenever it is justified that design extra costs imply greater manufacturing savings the design should include the requirements offering these savings.
- When design or equipment reuse philosophy, or COTS equipment acquisition are part of the design rules it is hardly complicated to modify the design in order to add new requirements based on manufacturing needs.

However, when collaborative engineering is correctly set up, results justify the effort made during early design phase. Hereafter are presented some examples of implementations carried out in the A400M.

In the frame of the A400M program, special attention was given to testability and accessibility requirements during systems design phase. Considering the A/C systems architecture, available technologies and their capabilities and the testing needs during A/C manufacturing phase at FAL, specific functions were integrated into A/C systems in order to:

- improve aircraft systems testability on ground,
- reduce ground tests time, cost and non-quality issues,
- extend and adapt the CATS® test system capabilities,
- increase integration level between CATS® test system and A/C systems.

The A400M systems architecture is based in an AFDX network connecting A/C systems. This network contributes to a high level of integration between systems and eases the definition of communications between A/C systems, but also between A/C systems and non-onboard systems like CATS®.

The importance of the AFDX network is based on the fact that communications can be easily defined without hardware installation impact on A/C. The modification of the network configuration by installing new software in the AFDX switches allows the definition of new communication links between A/C systems.

The second key point to be considered regarding the A400M systems architecture is the Network Server System (NSS) platform. The NSS platform is the A/C system used basically to host the maintenance applications such as the Centralised Maintenance System (CMS), the Dataloading and Configuration System (DLCS) or the Aircraft Condition and Monitoring System (ACMS). The key aspect of the NSS is that every A/C system communicates with the NSS, which means that communication links are already defined between the NSS and any other A/C system for A/C functional purpose.

This architecture eases the definition of specific information exchange for ground systems tests during A/C manufacturing. For that, two requirements were considered during design phase:

1. A/C systems implement a dedicated function that allows sending ground tests information to the CATS® ground test system through the NSS platform.
2. The NSS platform implements a specific function to behave as a gateway between A/C systems and the CATS® system, forwarding A/C systems messages to a dedicated AIM called NSSAIM.

In order to avoid certification and security issues, the NSS platform does not implement this gateway functionality in normal operational configuration. For that, a specific test software configuration is installed during A/C manufacturing at FAL in the NSS platform, which is replaced by the operational configuration before A/C delivery to the customer. Figure 12 displays the connection of CATS® to the A/C making use of different AIMs, one of which is the NSSAIM connected to the NSS platform as already described.

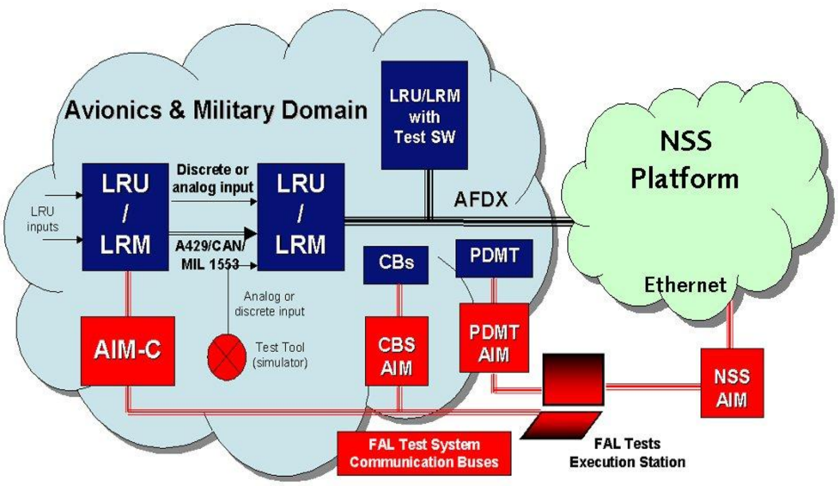

Figure 12. CATS® Test System Connection to A/C.

Another way of taking advantage of A/C systems for improving ground testability is making use of already implemented functions on A/C for an additional purpose for which these functions were originally conceived. The Network Bite Function (NBF) is a software application running in the NSS platform, in charge of monitoring AFDX network status and reporting system faults. The system works based on the well-known SNMP (Simple Network Management Protocol) communications networks protocol. The NBF is continually polling every AFDX subscriber in order to retrieve information about their status by making use of the SNMP protocol. The protocol defines commands and responses to get information from the subscribers' MIB (Management Information Base), which records different objects (values).

How can the CATS® system get information from the AFDX subscribers' MIB? The only requirement to be considered is the gateway functionality in the NSS platform, in order to allow CATS® transmitting SNMP requests and receiving the answers from the AFDX subscribers. This function could be extended by adding new objects to the subscribers' MIB with useful information for ground tests during manufacturing, but this should imply modifying AFDX subscribers' MIB, which should be carried out as already explained by collaborative engineering during early design phase.

Finally, a third example of how collaborative engineering together with new technologies and systems architectures contributes to improving ground testability is given hereafter. The A400M flight control system is one of the most complex systems on board the A/C, making use of fly-by-wire technology. The system has also evolved to the MEA concept and uses Electro-Hydrostatic Actuators (EHA) that locally convert electrical power into hydraulic power to produce the movement of the actuator. Primary and secondary flight control computers, connected to several actuators and sensors for flight control surfaces actuation and monitoring, are the heart of the system.

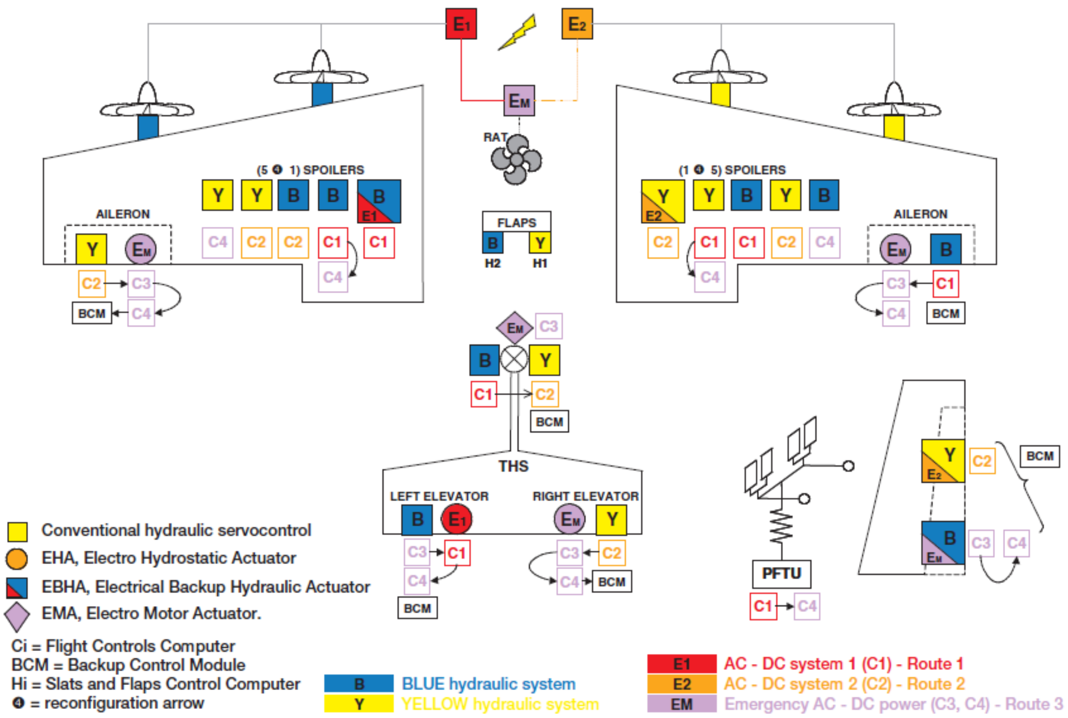

Figure 13. A400M Flight Control System.

Indeed, the system testing should check that every single actuator and sensor works correctly in the different possible modes, which is not easy to achieve by simply operating the system.

For improving the system testability, a specific test mode function was developed in the flight control computers. This test mode allows the CATS® ground test system to communicate with the flight control computers making use of the NSS platform gateway function thanks to the MICBAC (Micro System Bus Access Channel) MK3 protocol. The MICBAC MK3 protocol is an Airbus request-answer based protocol defined to facilitate A/C testing at FAL.

The protocol defines the format of the commands and answers that can be sent over the AFDX network to establish a dialogue between the A/C computer and the ground test system. The commands allow:

- the activation of the test mode in the target computer,
- reading any A429, CAN, discrete, analog and AFDX inputs and outputs of the target computer,
- setting any A429, CAN, discrete, analog and AFDX output values,
- sending complex commands to activate predefined test functions.

For safety reasons, the test mode function can only be activated under certain conditions. In the case of the flight control computers, it is requested to connect a hardware key that sets to ground a group of discrete input signals to the computers. Then, a specific MICBAC MK3 command with a predefined password must be sent to the computers to enter into test mode. In other cases, the test mode function is developed as specific test software that needs to be dataloaded in the computer and replaces the operational software, therefore safety requirements do not need to be considered as far as the software is not part of the A/C configuration and does not need to be certified. Once ground tests are finished the operational software is dataloaded and the A/C is set in operational configuration.

The test mode of the flight control system has been designed in such a way that it is able to move any given control surface by making use of any of its associated actuators. This allows the testing of the complete system exhaustively, and also, in case of actuators replacement or wiring rework, the test of the involved system parts or components only.

Moreover, once the test mode function is developed and the A/C allows communicating with it, it is possible to develop specific ground test applications not necessarily to be used during manufacturing phase. In the case of the flight control system, a tool called CDV (Commande De Vol) Tool has been developed by Airbus in order to make use of the MICBAC MK3 protocol and the test mode function in the flight control computers. This tool takes advantage of the defined functionalities on board the aircraft to test the flight control system on ground, even when the A/C is not at FAL. For instance, the tool can be used for in-service tests during A/C maintenance. It is obviously concluded that advantages on systems design can be extended to the complete A/C life, taking into account that tests will be required in many different circumstances.

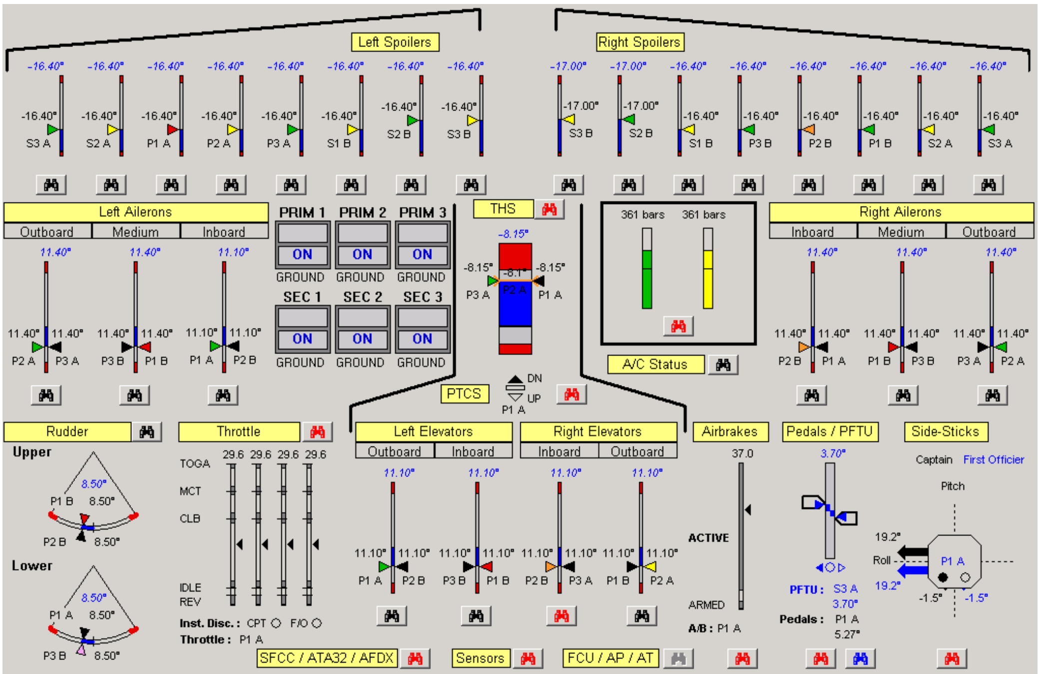

Figure 14. A380 CDV Tool.

6. Conclusions and future in testability

High level of on-board systems integration and high communication capabilities allow, if correctly and in-time defined, more efficient manufacturing processes in terms of testing, with important non-recurrent and recurrent costs and time saving. Collaborative engineering during early A/C design phase between the different involved teams (design, installation and manufacturing engineering) is basic for reaching optimal results regarding product design, integration and manufacturing, which includes testing.

Moreover, on-ground testability improvements for manufacturing can also be used during in-service A/C life for maintenance activities. Considering how important A/C maintenance is and that reducing maintenance time and costs is one of the priorities of A/C operators it is worth taking advantage of collaborative engineering for defining on-ground testability requirements either for manufacturing phase and or in-service phase. Important advantages and savings can be obtained if systems design consider from the very beginning testability requirements.

Currently, Airbus Military is working in the FSP20 (Futuro Sistema de Pruebas 2020) project, as part of the Feder-Innterconecta program funded by the European Union. The FSP20 project is an R+D project launched in 2012 that will finish in 2014, whose main objective is the research and development of new technologies, architectures and solutions for improving A/C on-ground testability. As part of the results to be obtained within the project, specific A/C systems architectures and solutions will be given to provide with predefined solutions to systems designers and suppliers in order to take advantage of systems implementations during manufacturing ground tests.

The future should lead to standardisation of aircraft systems capabilities and functions for ground testing, either at FAL or during A/C in-service maintenance, leading to more and simpler integration between A/C systems and ground testing tools with easy connection capabilities and standard protocols and solutions utilisation.

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