A Review of Aeronautical Electronics and its Parallelism with Automotive Electronics

J. Muñoz-Castañer, R. Asorey-Cacheda, F.J. Gil-Castiñeira, F.J. González-Castaño, P. S. Rodríguez-Hernández

***Abstract*—Aeronautical electronic and communications technologies have evolved from the analog domain to the digital domain and, nowadays, planes are complex structures serviced by many standalone systems that communicate through data buses. Many of these systems have found applicability in other sectors. This paper reviews the most recent technologies in modern aircraft and identifies their application in the automotive sector. It also identifies automotive electronics applied in planes.**

***Index Terms*—Aeronautical electronics, automotive electronics, embedded systems.**

I. INTRODUCTION

THIS paper reviews the current state of the art of electronic systems in the aeronautic sector and their possible application in the automotive sector, and vice versa. The aeronautic sector has a long tradition in the development of advanced electronic systems, pioneering the replacement of mechanics by electronics to improve performance and achieve new functionality [1]. The number of systems that can be found in a latest-generation passenger plane is really impressive. These systems include components, hardware and software architectures, development tools, applications, and so on.

Although there exists literature about different technological aspects of the aeroespace and automotive industries [1]–[6], to the best of our knowledge there is a lack of analyses on the links between these two industries in the area of electronics. This paper aims to identify the links that have led, or may lead, to cross-technology transfer.

It is obvious that technology transfer has typically taken place from the aeronautical industry to the automotive industry [7], [8]. However, there are exceptions to this rule and, in some cases, some technology advancements appeared first in automobiles and, after their success, were transferred to aircrafts [9]–[11]. It is therefore likely that future advancements will appear almost at the same time in both industries.

This document is organized as follows: In section II, we review the electronic systems that are used in aeronautics and their relationship with the automotive sector when applicable. In section III we identify and describe the main in-vehicle communication standards in both sectors. Section IV provides perspective on the evolution of technology transfer. Section V concludes the paper.

II. AIRCRAFT ELECTRONICS AND AUTOMOTIVE EQUIVALENTS

In addition to companies involved in implementations of a particular system, there are many companies engaged in virtually the entire range of embedded systems in a plane. In the automotive industry for example, sometimes the products are manufactured by small companies and sold under the brands of a larger enterprise. The major players are BAE Systems [12], Curtis-Wright [13], EADS [14], Goodrich Corporation [15], Honeywell [16], ITT [17], L-3 Communications [18], Lockheed Martin [19], Northrop Grumman [20], Raytheon [21], Rockwell Collins [22], Thales Group [23], and United Technologies Corporation [24].

A. Head-Up Displays (HUD)

In fighter planes, HUDs help the pilot to mantain his concentration by providing relevant flight information in his field of vision. When the device is mounted on a helmet, it is called an HMD or *Head-Mounted Display*.

An HUD is a transparent display that is installed between the pilot and the canopy on which information is projected as in a television *prompter*. The information displayed may be static, such as speed and altitude, or dynamic, such as the inclination of the horizon, the direction of the north or the position of a target.

Several problems had to be overcome for this system to work, such as avoiding object reflections on the display or calibrating the projected image so that the pilot can focus on an image outside the aircraft and the displayed information simultaneously. It is also important that information is the same under different light conditions. Finally, it is necessary to take into account the parallax error by varying the observer's position with respect to the HUD and the outside.

It is possible to find examples of these systems on the the websites of Esterline CMC Electronics [25] and Elbit Systems [26].

This concept has not been extensively exploited in the automotive world. HUDs are relatively bulky devices due to the projector characteristics, and may be uncomfortable for a car driver. Among the advances in the automotive world regarding lightweight transparent screens we can mention those of Magneti Marelli [27], as well as the projection on the windshield by Continental [28] or in the Citroën C6 [29]. The projector can also be linked to a GPS, as in the case of Asus R710 [30].

J. Muñoz-Castañer, R. Asorey-Cacheda, F.J. González-Castaño, P. S. Rodríguez-Hernández and F.J. Gil-Castiñeira are with the Departamento de Enxeñaría Telemática, Universidade de Vigo, ETSE Telecomunicación, Campus, 36310 Vigo, Spain, tel.: (+34) 986 814 081, fax: (+34) 986 812 116, email: jorgem@det.uvigo.es; rasorey@det.uvigo.es; xil@det.uvigo.es;javier@det.uvigo.es; pedro@det.uvigo.es.

B. Line-Replaceable Unit (LRU) and Integrated Modular Avionics (IMA)

Current on-board plane electronics consist of a set of sensors/actuators and several computing units called Line-Replaceable Units (LRU) [31]. These units are black boxes that can be easily removed and replaced in case of failure. An LRU is composed of several Line-Replaceable Modules (LRM), which are commonly commercial off-the-shelf (COTS) or application-specific integrated circuits (ASIC) with computing capabilities.

Latest-generation commercial aircraft such as the Boeing B-777 [32] or the Airbus A380 [33] and combat aircraft follow a different approach called Integrated Modular Avionics (IMA) [34]. The goal is to reduce the number of LRUs and wiring in the plane by integrating multiple functions in the same hardware. The B-777 AIMS system, for example, uses two modules to perform all the data acquisition, computation and management of the Electronic Flight Instrument System (EFIS).

In the automotive industry, Electronic Control Units (ECU) [35] are a close equivalent to LRUs. These units are used to manage systems such as airbags, doors and engines. The first ECUs were introduced by General Motors in 1981. However, despite obvious similarities between ECUs and LRUs, so far there has not been an integration process such as that that led from LRUs to IMAs. For this reason, modern automobiles may have up to 80 ECUs, so it is possible that other systems with a higher level of integration will appear in the future.

C. Control Panel

The control panels in military or commercial aircrafts are very similar, technologically speaking, due to the tendency to use COTS systems. The control panel of an airplane, like that of a land vehicle, presents information on its status and allows the pilot to interact with several flight parameters.

A new trend in the aviation sector is to replace analog monitoring devices other than backup devices with digital LCD screens. Examples of companies that are engaged in this sector are Airbus [36], Aspen Avionics [37], Blue Mountain Avionics [38], Dynon Avionics [39], Esterline CMC Electronics [40], Garmin [41], Innovative Solutions & Support [42], J.P. Instruments [43], MGL Avionics [44], Rogerson Kratos [45], Sandel [46], Universal Avionics [47] and Zodiac [48].

ARINC has pushed for the production of standards for connecting control planes to airplane systems through the *Cockpit Display Systems (CDS) Subcommittee* [49]. There also are efforts to standardize the graphical interface software embodied in ARINC Specification 661 [50]. An example of integrated development environment (IDE) that supports this standard is PRESAGIS VAPS XT [51].

Integrating touch screens in aircraft control planes is challenging because it is not possible to provide rapid feedback to the user, who cannot concentrate on the screen. A possible solution is the use of haptic displays. These screens have piezoelectric devices that can vibrate, providing tactile feedback to the user, such as the position of a button or acknowledging that the button is pressed [52]. Haptic technology is also present in the automotive sector [53], [54] (for example in BMW Series 6 and 7), where it is used for the same purposes as in aircraft.

D. Enhanced Vision Systems (EVS), Enhanced Flight Vision Systems (EFVS) and Synthetic Vision Systems (SVS)

These systems offer an enhanced representation of reality at night or in foggy weather using infrared or thermal cameras and machine vision algorithms. The websites of Gulfstream [55] and Kollsman [56] provide an illustration of these systems.

Such systems could be useful to the automotive sector to improve driver safety. Magneti Marelli is already conducting investigations in the field of night vision [57] and the recognition of traffic signals [58]. The Mercedes Benz S-class W221 and the BMW 7 also have night vision systems [59]. In the case of Mercedes, the display is placed in the speedometer, whereas in the BMW it is placed in the center of the dashboard. Thus, in both cases the driver must look away from the windshield.

Another environment enhancement system is SVS, which represents a three-dimensional view of the plane's surrounding. It is complemented with a positioning system to place the aircraft on the map. It allows the pilot to check visual references and it can also detect if the aircraft is in danger of collision. More information is available at the official websites of Chelton Flight Systems [60], Garmin [61], Honeywell [62] and MetaVR [63]. This concept could eventually be applied to a car if alternative graphical representations of reality were available. For example, Blusens has marketed a GPS navigator [64] that uses city pictures instead of 2D maps.

E. Data Acquisition Systems, Software Data Loader

A plane must collect information from many sensors on status and navigation data, often for further treatment. There are data collection systems based on magnetic vibration-proof hard drives or solid-state hard drives. These systems have common interfaces such as Ethernet, RS-232, MIL-1553B, ARINC-429, audio, video, analog/digital converters, etc.

The *Digital Flight Data Recorder (DFDR) Subcommittee* [65] and the *Flight Recorder Electronic Documentation (FRED) Subcommittee* [66] of ARINC seek to define standards for data collection. It is possible to find references on these systems in the pages of companies such as Adtron [67], Ametek [68], Ampex Data Systems [69], Ampol [70], Meggit Avionics [71], Seagate [72], Signatec [73], Silicon Systems [74], STEC [75], Vanguard [76] and Z Microsystems [77].

Regarding data acquisition systems in the automotive sector, possible applications are diverse. In public transport there are compulsory data loggers to be cited as legal evidence in case of accident. For private vehicles, there are data collection applications such as Fiat ecodrive [84], which collects data in a USB stick for a computer application to advise on how to improve driving abilities.

The Software Data Loader (SDL) system is responsible for receiving software and installing it in aircraft equiooment. The *Software Data Loader (SDL) Subcommittee* [78], the *Electronic Distribution of Software (EDS) Working Group*

[79] and the *Field Loadable Software (FLS) Working Group* [80] are creating standards to facilitate interoperability of equipment from different manufacturers. For example, the ARINC-826 specification supports software load through a CAN bus. The ARINC-615 specification defines a portable device that contains the new software, which is taken onboard to load updates. This technology is described in the pages of Avionics Companies [81], Demo Systems [82] and Teledine Controls [83].

Despite the fact that cars are short-lived goods compared to aircraft, given the increasing importance of electronic equipment as a major source of car value, some sort of SDL system to fix bugs may be advantageous. In some market segments users would appreciate the possibility of tuning performance by downloading signed firmware. Of course, this feature should be used carefully and it may require the development of new technologies that would not allow inexperienced users to change critical parameters.

F. In-Flight Entertainment (IFE) and Multimedia Systems

These systems can be local or provide connectivity with the outside world. There is a forum of companies related to IFE called the *World Airline Entertainment Association* (WAEA) [85] that provides some degree of standardization in this field.

Multimedia systems allow passengers to enjoy multimedia content in their seats. IFE systems include:

- Movie players, television, music, audio books or electronic books provided by the carrier.
- Synchronization of user devices with the systems to play user content.
- Games.
- Information on flight status: Position on a map, arrival time calculation, video playback of external cameras on the airplane, etc.
- Request for meals/drinks and card payment in the seat.
- Service messaging between users in the cabin.
- Web surfing in a cache if there is no connectivity.

Some users of IFE systems are Emirates Airlines [96], Virgin America [97] and Singapore Airlines (KrisWorld) [91]. For example, Singapore Airlines employs the Panasonic eX2 system, which consists of a content server and seat displays associated with embedded PCs with Linux-based operating systems. These PCs also have a small QWERTY keyboard and USB connectors to access external disks, and they run office applications [92].

Major IFE manufacturers are Thales IFE systems [88], Panasonic [89] and Rockwell Collins [90], [93], [94]. Other manufacturers are Airvod [98], AlsterAero [99], Avionics Innovations [100], Digecor [101], Flight Display Systems [102], Groupe Latecoere [103], InFlight Entertainment Products [104], The IMS Company [105], Intheairnet [106], Lefeel [107], PGA ELECTRONIC [108], Skygem [109], and Videon Central [110].

As a further enhancement, these systems may help the airline by collecting data about customer preferences to improve service progressively. Other improvements are related to weight, power savings and interference minimization. For instance, Lumexis [95] uses optical fiber to transport flows.

The most widespread multimedia system for cars consist of DVD players connected to back-seat screens. Like IFE systems, some multimedia solutions for coaches rely on a central server, which serves multimedia content to luggage rack screens [87]. High-end cars like the BMW 7 Series [86] employ external cameras to assist driving in narrow areas (as trucks do), which may evolve for entertainment purposes. In any case, multimedia system manufacturers for the automotive and aeronautical sectors employ the same COTS-based solutions to save costs.

G. Electronic Flight Management

The Electronic Flight Management system provides flight planning support and navigation capabilities, such as path prediction and guidance. Flight planning consists of establishing the route of an aircraft and modifying it if necessary. It is based on the configuration of waypoints. Path prediction calculates the position of the aircraft in the flight plan according to weather conditions and aircraft performance. The system maintains a database of weather conditions and characteristics of aircraft models. From the flight plan and the path predictions it is possible to calculate the duration of a trip and optimize fuel consumption. These plans can guide the pilot along an optimized route.

The EFM system typically consists of two functional units called the computing unit and the display control unit. The computing unit may be a separate unit that provides computing capability and interfaces with other systems, or it may be embedded in an IMA system. The display control unit provides the human-to-machine (HMI) interface. Beacon sensors or intertial reference systems allow to calculate the height and the velocity vector, so the plane can be located on a geographical point even if GPS contact is lost. Relative position error will depend on the tolerance of the sensors and increase with time, but the precision is acceptable in critical situations.

Therefore, this system requires the participation of diverse location sensors and engine-monitoring devices to perform its tasks.

There are references to these systems in the websites of Esterline [111], GE Aviation [112], Honeywell [113], Rockwell Collins [114], Universal Avionics [115] and Flight Management Systems [116].

In the automotive sector, GPS navigators play some roles of EFM systems. Borrowing key ideas from the aeronautical sector, some navigators, such as the Tom Tom Go 920 [117], keep working in areas without GPS coverage by using motion sensors to calculate the position of the car temporarily.

H. Electronic Flight Bag (EFB)

The EFB is a portable device that contains useful information such as manuals or maps which is compulsory to take on board. With EFBs, information can be updated easily and synchronized with other aircraft systems such as EFM to coordinate routes.

Despite their portability, these devices depend on the type of aircraft. For this reason, ARINC is standardizing the interface between the EFB and different aircraft systems [118].

Some companies that manufacture EFBs are DAC International [119], EFlyBook [120], Esterline CMC Electronics [121], Gulfstream [122], NavAero [123], Teledine Controls [124] and Honeywell [125].

Regarding the automotive sector, it would be interesting to let drivers design routes on home PCs and download them to mobile devices such as cell phones to be uploaded to embedded GPS navigators in the car. This concept was described in [126].

I. *Vehicle Health-Monitoring System (VHM)*

The basic purpose of this system is to determine whether the operational state of a system is as expected. Once determined, this knowledge is used to mitigate the impact of detected failures or, at least, to report the event. The system can be ordered to reconfigure itself to isolate faulty elements. Although aircraft subsystems can separately implement redundancy or fail safe coding techniques, the VHM can, in some way, coordinate them.

The first commercial aircrafts carried mechanical and electrical systems. Health-monitoring tests consisted of pressing a button to close a circuit which, in turn, lit a bulb on the dashboard. If the bulb did not light up, it revealed a problem. With the advent of digital systems in the early 80s, these tests were replaced by panels dedicated to LRUs where it was possible to check their status. With the proliferation of LRUs, learning the procedures to test all systems was overwhelming. To solve this problem, the ARINC-604 document *Guidance for Design and Use of Built-In Test Equipment* [127] was issued in 1985 to standardize and centralize LRU tests. The subsequent ARINC-624 document *Design and Guidance for Onboard Maintenance System* [128] defines a device called a Central Maintenance Computer (CMC) or Onboard Maintenance System (OMS) that performs verifications and traces the origins of the failures. This centralized system facilitates the diagnosis of IMA-based systems.

The *Open Systems Architecture for Condition-Based Maintenance* standard (OSA-CBM) [129] was initially developed for US Navy ships and later adopted in ground and aerial vehicles. It defines a layered architecture. The lowest layer consists of sensors and data flows to the highest layers, where decisions are made. This architecture allows interoperability among device makers at different levels.

Both ARINC-624 and OSA-CBM define the Integrated VHM (IVHM) architecture [130]. An example of a representative IVHM system is the Aircraft Maintenance Diagnostic System (ADMS) from Honeywell [131]. This system is integrated into the Honeywell Primus Epic system, an IMA for airplanes and helicopters that entered service in 2003. ADMS supports over 200 vehicle subsystems, providing a single access point for diagnosis with a graphical interface. ADMS can also perform diagnostics alone, indicating the root of the problem.

Both ADMS and another IVHM system, the *Crew Information System* of the B-787 [132]), can autonomously submit aircraft data down to earth through a communications link, to be analyzed by more powerful diagnostic systems based on artificial intelligence.

In the automotive sector, VHMs are widely used in professional races such as Formula 1 in a similar way to in the aeronautical industry. Another automotive approach to VHMs are On-Board Diagnostic (OBD) systems, which were introduced in the early 80s and are present in practically all modern commercial automobiles [133], [134]. However, OBD interfaces are simpler than VHMs as they provide local information only. However, there are proposals to use them for remote monitoring of private [135] or commercial vehicles [136].

J. *Fly-By-Wire*

X-By-Wire (XBW) systems, of which Fly-By-Wire is a particular case, replace the mechanical transmission between control systems and steering systems. This leads to weight reduction and assisted driver control, and it even allows extremely maneuverable planes to be flyable.

The first systems of this kind were implemented in the late 70s and early 80s. They transmitted signals that were proportional to the force exercised by the pilot at the controls. They were also responsible for providing feedback to the pilot in the form of pressure on the controls.

Latest-generation planes, such as the Boeing B-777 [32] or the Airbus 3X0 [137]–[139], have more advanced systems based on digital technology. We will focus on these systems in the rest of this section.

The Fly-By-Wire architecture, or FBW, consists of a series of electromechanical actuators that operate the moving parts of the aircraft, a set of sensors that transmit information on their state and position and numerous devices with computing capabilities that are responsible for converting the signals from the pilot into orders for the actuators and communicating with other aircraft systems such as EFM. Usually the system is supported by an ARINC-629 bus or by an ARINC-429 bus for point-to-point connections.

One of the most important requisites in an FBW system is fault tolerance. The main approach is making critical components redundant and placing them in separate parts of the airplane. To decide which of the replicated signals to use, it is possible to utilize a voting system. The fact that one order is beyond a threshold established for the majority of the devices is a clear sign of dysfunction. Another possible approach is to use one device as a master and another as a monitor. These would be functionally identical but have different hardware and software architecture, so a failure of either or poor implementation would not result in a complete system collapse.

The automobile industry has spent years pursuing technology similar to XBW technology but called Drive-By-Wire. It decouples driver controls, steering systems and engine systems, enabling new features such as the capability of assuming driving in situations that may endanger the integrity of the car (e.g. ABS) or cause passenger discomfort. This technology could be combined with haptic controls [140]–[142], for example to alert the driver when the car approaches

TABLE I
SUMMARY OF AERONAUTICAL TECHNOLOGIES AND THEIR EQUIVALENTS IN THE AUTOMOTIVE SECTOR

	Aeronautical	**Automotive**
Data buses	There exist many different standards. Present in all planes.	The automotive industry has developed its own standards. Some of these standards have been adapted to the aeronautical industry.
Control panels	Highly standardized. Current trend is to substitute analog panels by digital ones. Interest in haptic technology	Current trend is to use digital control panels instead of analog ones. Haptic technology has also been introduced, to a lesser extent.
EVS, EFVS and SVS	There exist several systems for aircraft navigation and collision warning	Marginal interest, given that cars move in a 2D scenario.
HUD displays	Mainly in military aircraft.	There exist some developments, but technical advancements are still necessary to achieve commercial status.
Entertainment & multimedia systems	Present in modern commercial aircraft. Client-server architecture. Some business applications	Back seat screens for cars (integrated architecture), luggage rack screens for coaches (client-server architecture).
Electronic Flight Management	Present in all planes.	GPS navigators provide some EFM-like features, but with some limitations.
Electronic Flight Bag	Present in many planes, but not standardized yet.	Some existing proposals [126].
Vehicle Health Monitoring System	Present in both commercial and military aircraft since the 80s.	There exist some proposals [135], [136]. OBDs as enabling technology.
X-by-Wire	Present in aircraft since the late 70s.	Similar technologies have been developed for the automotive sector, specially for safety (e.g. ABS).

the speed limit, by hardening the accelerator pedal, or in case of a wet road, by changing the touch of the steering wheel.

Table I summarizes the aeronautical electronic technologies in our review and their equivalents in the automotive world. As can be observed, many of the technologies deployed in aircrafts have equivalents in the automotive sector but at different stages of development.

III. INTERNAL COMMUNICATIONS

In the 50s and 60s all aircraft electronics were analog systems. In the 70s, manufacturers started to install digital computers to assist pilots in some tasks, although most internal communications were still analog. It was necessary to add A/D converters so that computers could understand the signals.

Economies of scale allowed the massive entry of digital components into aircrafts, as happened with cars. However, subsystem interfaces became increasingly complex. The first step was a star topology with point-to-point connections between central and edge subsystems. This proved to be cumbersome. The weight of cabling and interface cards compromised scalability.

For this reason, there was a trend towards the use of redundant serial buses (rather than parallel ones). The need to standardize these buses was soon noticed and, in 1973, the USAF MIL-STD-1553 standard was issued. In 1975, a second version, MIL-STD-1553A, was published. In 1978 the third and current version, MIL-STD-1553B, was launched. It is still in use, with some changes, in almost all military aircraft. On the other hand, the United Kingdom created the Def Stan 00-18 series of standards, which also covers most military aviation interfaces.

Commercial aviation representatives collaborated in the development of MIL-STD-1553, but it eventually proved too demanding for commercial use. Thus, they developed their own standard, whose first description is ARINC Specification 419. Due to the need for improvements, ARINC-429 was launched in 1977. It became a reference, remaining largely unchanged until 1980. This standard is equivalent to MIL-STD-1553 in terms of success, and it has also been applied in other industrial sectors.

Currently, aeronautical systems require higher bandwidth than those standards can offer. Consider, for example, the need to transport multimedia streams, or simply the difference in computing capabilities between current equipment and that of the 80s. The first reaction was to introduce new faster standards, such as new versions of MIL-STD-1553, but the success of ATM or Gigabit Ethernet led to the evaluation of COTS technologies for avionics. Of course, consumer electronics solutions do not meet the stringent requirements in aeronautical applications, so better alternatives have been proposed such as AFDX, *Avionic Full-Duplex Switched Ethernet*, or TTCAN, *Time Triggered CAN.*

A. *Strictly military or commercial aviation bus standards*

- *MIL-STD-1553B standards*:
  - *MIL-STD-1553B*: The MIL-STD-1553B standard [144] defines the following architecture elements:
    - ∗ *Bus Controller (BC):* Bus node designated to direct the flow of data on the bus. Although there may be multiple nodes on the bus that can perform this task, only one is permitted to act as the bus controller.
    - ∗ *Remote Terminal (RT):* Nodes that are neither drivers nor bus monitors. They usually correspond to the hardware that interacts with the bus subsystem to exchange information.
    - ∗ *Bus Monitor (BM):* Bus node designed to collect all the information that passes through the bus or part of it. There may be several bus monitors. The information collected is used for offline applications or to detect bus failures, which allows the implementation of countermeasures such as the activation of an auxiliary bus.

  The various bus nodes are interconnected by redundant twisted wire pairs, with impedances at the ends. This technology allows bus lengths up to 6 meters if the nodes are coupled to the bus through a transformer, and about 30 centimeters if coupled directly. The same bus can address up to 31 different nodes or all of them at once with a *broadcast* address.

  The following companies implement this protocol: Excalibur Systems [145], Ballard Technology [146], Data Bus Products [147], Greenwood Electronic Components Ltd [148], ITCN [149] National Hybrid, Incorporated [150], North Hills Signal Processing [151] and Phoenix Logistics [152].

- *Extended MIL-STD-1553:* In the early 90s, the US DoD had to change the protocol buses in combat planes. While MIL-STD-1553B was sufficient to handle the weapon system with its 1 Mbps speed, it could not support radar and computer display signals, which require from 20 Mbps to 200 Mbps. Since the cost of replacing the wiring of operational aircraft was prohibitive, the ideal solution was to reuse existing wiring.

  One of the earliest attempts was called NG1553, *Next Generation 1553*. This proposal was intended to increase the clock speed of the hardware to achieve a fivefold bit rate. NG1553 was used in modest applications and it was not a long-term solution.

  The Canadian company Edgewater Computer Systems [153] presented at the beginning of 2000 the *Extended 1553* or, simply, e1553, which allows speeds of 200 Mbps. E1553 is similar to DSL protocols in the sense that it is a multicarrier protocol compatible with existing 1553B equipment.

  In 2006, the e1553 standard became part of MIL-STD-1553B with the publication of MIL-STD-1553B Notice 5.
- *AS5662:* The AS5662 standard is another variant of MIL-STD-1553B [154]. It reaches a 10 Mbps speed. In a star topology, the bus controller acting as a hub can connect up to 31 remote terminals. Alternatively, it is possible to connect the bus controller to 8 hubs and each hub to 31 remote terminals in turn. AS5662 does not allow message exchange between RTs. It is included as a standard network in the MIL-STD-3016 draft of the Miniature Munitions Stores Interface Task Group
- *Def Stan 00-18 (Part 3)* is a simplified version of Def Stan 00-18 (Part 2)/MIL-STD-1553B for point-to-point or point-to-multipoint connections [155]. It supports simplex, half-duplex and full-duplex links. Def Stan 00-18 (Part 3) preserves the physical layer specifications of MIL-STD-1553B and provides simpler message formats.
- *Other related standards*:
  - Def Stan 00-18 (Part 4): Defines several physical interfaces for different MIL-STD-1553B functions.
  - BSG 264/Def Stan 00-18 (Part 7): Low cost version of MIL-STD-1553B.
  - prEN3910/STANAG 3910/EFA Bus/EFA Express Bus: Defines a 20 Mbps optical network that is operated by a MIL-STD-1553B network, which restricts low-bandwidth devices to the twisted pair. This bus is used in the Eurofighter Typhoon.

- *ARINC-429* [156]–[158] is one of the standards used in passenger, cargo or military aircraft. When electronics manufacturers for commercial aircraft dismissed further development of MIL-STD-1553 because it was too demanding for their purposes at the beginning of the 70s, they looked for simpler alternatives for the transmission of digital data. They produced a collection of protocols based on a transmitter and multiple receivers, which were described in the ARINC-419 document. From those ideas, ARINC-429 protocols were developed and collected in 1977, and became an industrial standard.

  The first implementations of this standard were carried out in the Airbus A-310, the Boeing B-757 and the B-767 in the early 80s. These airplanes have about 150 buses that interconnect different displays, sensors, radios, controls and computers. With the exception of the buses connecting navigation computers at 100 Kbps, the data transmission rates were an order of magnitude lower.

  The ARINC-429 document was entitled Digital Information Transfer System (DITS), deliberately excluding the concept of data bus since the standard specified a one-way communication. ARINC-429 allows bus or star topologies, both with a single producer of data, although a return connection can be used to support full-duplex transmissions. The bus is an unshielded twisted pair, allowing a length of up to 50 meters at 12 Kbps or 100 Kbps.
- *ARINC-629* [159]–[161] was an attempt to improve the limited bandwidth and excessive wiring weight of ARINC-429. ARINC-629 grew out of Boeing's DATACE program, *Digital Autonomous Terminal Access Communication*, and became a standard in 1989. It is part of the implementation of the control and FBW systems in the Boeing 777.

  An ARINC-629 bus is a twisted pair terminated with impedances. The nodes are connected to the bus through a coupled cable of up to 40 meters. It is possible to connect up to 120 nodes to the same bus at a data rate of 2 Mbps.

B. Bus protocols of use in the aeronautical sector and the automotive sector

The aeronautical sector, especially the commercial subsector, has decided to adopt communication protocols that have proven to be successful in cars.

- *CAN:* While the automotive electronics industry has expanded considerably, the avionics electronics industry has developed at a mach slower pace, particularly in the area of military aircraft. The high competitiveness of the consumer market makes automotive electronics much cheaper. However, some of their requirements are similar to those of fighter planes. CAN devices can work in temperature ranges from -40^{o}C to 125^{o}C, not far from the military ranges from -55^{o}C to 125^{o}C.

CAN is a robust serial communication protocol that provides distributed control in real time. It was developed by Bosch in 1985. Although CAN was orginally developed for passengers cars, it was soon successfully used for industrial machine control, making standardization necessary. Currently, CAN fieldbuses are mainly used in the automotive industry, linking control units, sensors, safety systems, and other elements with data rates of up to 1 Mbps. Furthermore, it is a more advanced bus technology than MIL-STD-1553 and ARINC-429, enabling real-time communications and reducing system wiring. In fact, the CAN bus is used on Airbus aircrafts, including the A380, and by Boeing in the 787.

In CAN, since collisions are not destructive, low priority messages may starve. This is one of the problems that aeronautical implementations must overcome. For example, military implementations mostly require small physical layer level fixes. Some of these implementations are:

  - *MilCAN:* The Milco Working Group [162] was formed in 1998 as a subgroup of the International High Speed Data Bus Users Group of NATO. It recognized the need for standardization of the CAN bus of military vehicles. Milco is essentially a layer on top of ISO 11898.
  - *CANaerospace:* CANaerospace [163] was introduced in 1997 by Michael Stock Flight Systems [164]. It is used in the Eurocopter Tiger simulator [165]. It is an application layer on top of CAN. It specifies five types of messages but frees the user to define more types. It also covers bus redundancy.
  - *TTCAN* [166], which was developed in the early 2000s, solves the problem of starvation of low priority messages by means of CAN bus planning techniques, at the expense of lower data transmission speeds. In certain scenarios, such as XBW, a decrease in transmission rate is acceptable as far as there is a bounded delay in message reception. TTCA is based on a session layer that provides CAN-based communication time slots.

- *Time Triggered Protocol (TTP):* The TT architecture [167] has been studied for 25 years and there is extensive literature on operating systems, applications and data transmission protocols based on timing, as well as an organization that is responsible for its development called the TTA-Group [168]. There are two versions of the protocol, called TTP/A and TTP/C. The Society of Automotive Engineers, SAE, defines three types of communication systems according to safety requirements. Class A refers to low-speed systems such as window or seat checks or, in general, integration of transducers in a distributed control system. Class B is for high-speed systems without safety requirements. Finally, class C includes systems with high safety requirements and deterministic operation. Some examples of TTP/C are the digital bus for engine control of the Lockheed Martin F-16 or the cabin pressure control of the Airbus A380.
  - *TTP/C* defines bus, star or hybrid topologies of up to 64 nodes without a controller, which can transmit at speeds of up to 25 Mbps at distances of up to 120 meters. TTP does not specify the physical layer of the protocol, but assumes the existence of two independent redundant channels that can send different information if the safety requirements are not critical.
    The upper layers of TTP/C provide security services, health node monitoring and fault-tolerant services.
  - *TTP/A* does not define a physical layer, but it needs a two-channel bus. The bus supports up to 255 nodes. One of the nodes is the master and handles signaling when transmission begins.
- *IEEE 1394/FireWire:* FireWire, created by Apple in 1986 and an IEEE standard since 1995, supports a rate of hundreds or thousands of megabits per second. It is used in commercial products such as camcorders for isochronous multimedia streaming. In 2004, the avionics division of SAE AS5643 proposed the IEEE-1394b standard, *Interface Requirements for Military and Aerospace Vehicle Applications*, to be adopted in military vehicles [169]–[171].
  Summing up, an IEEE 1394 bus allows up to 1023 nodes connected in a chained or tree topology with up to 63 nodes per bus, using a shielded cable with two twisted pairs and power cables. The medium access schema follows a question/answer architecture that prevents starvation of distant nodes and allows hot-plugging. It provides two classes of service, for synchronous and asynchronous data transfer.
  The F-35 Joint Strike Fighter employs IEEE 1394-like protocols to connect diverse systems such as its control system and the VHM.
- *Ethernet:*
  ARINC created the *Network Infrastructure and Security (NIS) Subcommittee* [172] to adapt commercial network standards to the aviation industry and to face emerging bandwidth needs of cabin applications.
  - *ARINC-664* is the main initiative of this subcommittee. This document attempts to adapt IEEE 802 and ISO OSI. It is organized as follows:
    ∗ Part 1 is an overview of the state of the art in telecommunications networks in the aviation industry as well as a glossary and a tutorial for the adaptation of commercial networks to aeronautics.
    ∗ Part 2 is an overview of the Ethernet standard and its relationship with avionics networks.
    ∗ Part 3 defines the services of transport and network layers of the Internet. It is useful for defining avionics protocols.
    ∗ Part 4 addresses the problem of Internet routing and its application in avionics networks.

TABLE II
SUMMARY OF AERONAUTICAL BUSES

Year	Standard	Topology	Aircraft models
1973	USAF MIL-STD-1553A	Serial	F-16 Fighting Falcon, F-18 Hornet
1977	ARINC-429	Serial	Airbus A-330, Airbus A-340, Boeing B-757, Boeing B-767
1978	USAF MIL-STD-1553B, Def Stan 00-18	Serial	F-20 Tigershark, B-52 Stratofortress
1985	CAN	Serial	Airbus A-380, Boeing B-787
1986	TTCAN	Serial	Unmanned Aircraft Vehicles (UAV)
1989	ARINC-629	Serial	Boeing B-777
1997	CANaerospace	Serial	Airbus A-380
1999	AFDX	Tree	Airbus A-380, Boeing 787, Airbus A400M, Sukhoi Superjet 100
2000	IEEE 1394b	Tree	F-35 Joint Strike Fighter

    - ∗ Part 5 provides guidelines for construction of networking components, hubs, switches, routers, repeaters and methods for network interconnection with the outside.
    - ∗ Part 7 defines a deterministic full-duplex Ethernet network for avionics, called AFDX.
    - ∗ Part 8 is a guide to protocols and interoperability with IP-based services.
  - *AFDX* [173]–[175] is a real-time implementation of ARINC-664 developed by Rockwell Collins for Airbus (see Part 7 above). Airbus is installing AFDX in critical safety areas. Boeing also plans to install fiber optic AFDX on its B787 Dreamliner.
    The AFDX Ethernet architecture follows a star topology that allows speeds of 10 to 100 Mbps. The nodes of the topology are connected to other subsystems of the aircraft and the center of the star is a switch that routes the Ethernet packets. It is possible to connect multiple switches in cascade to expand the network. AFDX specifies that the entire network must be duplicated to ensure its operation in case of failure. The upper AFDX Ethernet layers support diverse IP-oriented protocols such as UDP, SNMP and TFTP.

To sum up, Table II presents some of the communication bus standards under review, the year in which they were introduced, their topology and some aircraft models that employ them.

IV. TECHNOLOGY TRANSFER

From what we have seen until now, the mutual influence of the aeronautical and automotive industries is rather evident.

Figure 1 shows the gaps between the appearance of a given technology in aircrafts and its subsequent introduction in automobiles. Although the curves are nonlinear, the gaps have tended to decrease in recent decades. Some reasons why some technologies are first introduced in aircrafts and later appear in the automotive sector are:

1) Cost is relevant in commercial airplane design, yet much less relevant than in an end-consumer market.

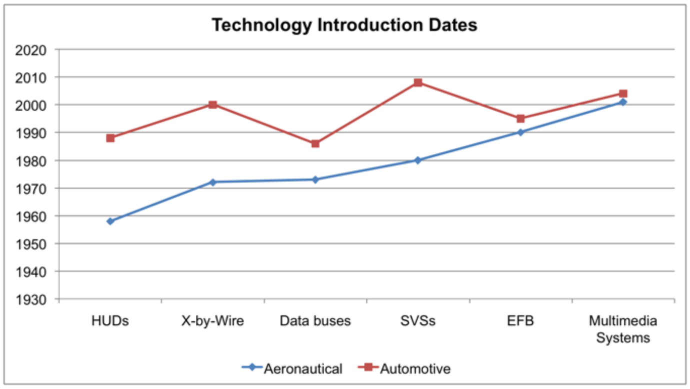

Fig. 1. Technology introduction dates for aeronautical and automotive sectors.

2) New developments reach the automotive mass-market later, when economies of scale make them economically feasible to or when new regulations make them compulsory. The time to market is shorter in high-end models and longer in cheaper models.

The progressively shorter gap between the aeronautical and the automotive sector can be attributed to the following:

1) Current innovation cycles are shorter. Eventually, the gap will be negligible. The technologies that first appear in the automotive sector might later be adopted in the aeronautics industry. We have seen a clear example in commercial data buses.
2) Many aeronautical companies are also present in the automotive sector [176]–[179]. This makes technology transfer a must to maximize profit.

Regarding internal communications, it is interesting to note two trends: an evolution from aeronautical-specific to common standards, and a progressive convergence with COTS technology towards protocols such as Ethernet and IEEE 1394b, despite the fact that the aerial platforms they serve are increasingly complex. Thus, it may happen that future bus standards will not be exclusive to the aeronautical sector. Their particular implementations for this sector will simply satisfy more demanding constraints than those of consumer electronics.

V. CONCLUSIONS

There is a clear tendency to use COTS systems in the aeronautical industry, compared to in-house hardware and software. Currently, there are too many electronic systems in an airplane and thus, it becomes very difficult for manufacturers to undertake the design and development of all their components. A consequence of this trend is the adoption of open standards to facilitate interconnection of modules from different manufacturers. For example, nowadays it is possible to find robust versions of CAN or Ethernet buses in aircrafts. As a consequence, it is now easier to find information about components for commercial and military aircraft. For example, the real-time CAN and Ethernet versions for avionics may be of interest for critical applications related to automotive safety.

The use of COTS systems has not diminished the need for high safety systems. The hardware/software products used in the aerospace and defense sectors must be qualified. These certifications are only granted to products that have undergone a design and manufacturing process according to safety standards.

We have seen how it is possible to borrow some interesting concepts for the automotive sector. We can cite the following:

- The design of modules that can accommodate several functions such as aircraft IMA in order to further reduce the number of ECUs in automobiles.
- Haptic feedback in car controls and devices such as steering wheels, pedals and radios.
- Fast visual access to information regarding the status of the vehicle without taking the eyes off the road, as in the case of fighter HUDs. This concept is already appearing in high-end cars.
- EFB devices that contain all the technical documentation. It has been proposed to use commercial nomadic devices to take data to cars [126].
- HMS systems. In fact, there are some initiatives in industrial transportation and high-end cars.
- Drive-by-Wire systems are now widely used in the automotive world. Further enhancements may include driving style personalization. These systems must fulfil stringent fault-tolerant specifications. The experience of the aircraft industry in fault-tolerant systems may be of great interest.

References

[1] J. A. Domínguez-Machuca, M. Sacristán-Díaz, M. J. Álvarez Gil, "Adopting and implementing advanced manufacturing technology: new data on key factors from the aeronautical industry," *International Journal of Production Research*, Vol. 42(16), August 15, 2004, pp. 3183–3202.

[2] A. Takeishi, T. Fujimoto, "Modularisation in the auto industry: interlinked multiple hierarchies of product, production and supplier systems," *International Journal of Automotive Technology and Management*, Vol. 1(4), 2001.

[3] M. Sacristán-Díaz, M.J. Álvarez-Gil, J.A. Domínguez-Machuca, "Performance measurement systems, competitive priorities, and advanced manufacturing technology: Some evidence from the aeronautical sector," *International Journal of Operations & Production Management*, Vol. 25(8), pp. 781–799, 2005.

[4] Y. Ward, A. Graves, "Through-life management: the provision of total customer solutions in the aerospace industry," *International Journal of Services Technology and Management*, Vol. 8(6), pp. 455–477, 2007.

[5] M. Persson, "Effects of changing a module's interface: a case study in an automotive company," *International Journal of Automotive Technology and Management*, Vol. 6(3), pp. 331–345, 2006.

[6] J. Batchelor, "Modularisation and the changing nature of automotive design capabilities," *International Journal of Automotive Technology and Management*, Vol. 6(3), pp. 276–297, 2006.

[7] J. Bereisa, "Applications of Microcomputers in Automotive Electronics," *IEEE Transactions on Industrial Electronics*, Vol. 30, pp. 87–96, 2007.

[8] S.K. Honey, W.B. Zavoli, "A Novel Approach to Automotive Navigation and Map Display," *IEEE Transactions on Industrial Electronics*, Vol. 34, pp. 40–43, 1987.

[9] P. Mariño, F. Poza, M.A. Domínguez, S. Otero, "Electronics in Automotive Engineering: A Top-Down Approach for Implementing Industrial Fieldbus Technologies in City Buses and Coaches," *IEEE Transactions on Industrial Electronics*, Vol. 56, pp. 589–600, 2009.

[10] R. W. Cox, "Local Area Network Applied to Automotive Electronic Communications," *IEEE Transactions on Industrial Electronics*, Vol. 32, pp. 327–333, 2007.

[11] G. Cena, A. Valenzano, "An Improved CAN Fieldbus for Industrial Applications," *IEEE Transactions on Industrial Electronics*, Vol. 44, pp. 533–564, 1997.

[12] BAE Systems. [Online]: http://www.baesystems.com/index.htm

[13] Curtis-Wright. [Online]: http://www.cwcembedded.com/

[14] EADS. [Online]: http://www.eads.net/1024/es/Homepage1024.html

[15] Goodrich Corporation. [Online]: http://www.goodrich.com/portal/site/grcom/home

[16] Honeywell. [Online]: http://www51.honeywell.com/aero/

[17] ITT. [Online]: http://defense.itt.com/

[18] L-3 Communications. [Online]: http://www.l-3com.com/

[19] Lockheed Martin. [Online]: http://www.lockheedmartin.com/index.html

[20] Northrop Grumman. [Online]: http://www.northropgrumman.com/about_us/electronics.html

[21] Raytheon. [Online]: http://www.raytheon.com/

[22] Rockwell Collins. [Online]: http://www.rockwellcollins.com/

[23] Thales Group. [Online]: http://www.thalesgroup.com/markets/Activities.html

[24] United Technologies Corporation. [Online]: http://www.utc.com/utc/home.html

[25] Esterline CMC Electronics. [Online]: http://www.cmcelectronics.ca/En/Prodserv/Head-Up-Displays-HUD–Weapon-Aiming.html

[26] Elbit Systems. [Online]: http://www.el-op.com/category/military_and_commercial_HUDs

[27] Magneti Marelli. [Online]: http://www.magnetimarelli.com/english/electronic_display_trasparente.php

[28] Continental. [Online]: http://www.vdo.es/products_solutions/cars/infotainment/augmented-guidance/

[29] Citroën C6. [Online]: http://www.citroen.es/CWE/es-ES/RANGE/PrivateCars/C6/HomeC6/

[30] Asus R710. [Online]: http://www.asus.com/product.aspx?P_ID=vvieZpVT33ECwj2e

[31] Curtiss Wright. [Online]: http://www.cwcembedded.com/4/188/375.html

[32] Boeing B-777. [Online]: http://www.boeing.com/commercial/777family/background/back6.html

[33] Diehl Aerospace, Integrated Modular Avionics. [Online]: http://www.diehl-aerospace.de/index.php?id=1330&L=1

[34] Avionics Magazine, Integrated Modular Avionics: Less is More. [Online]: http://www.aviationtoday.com/av/categories/commercial/8420.html

[35] N. Navet, Y. Song, F. Simonot-Lion, C. Wilwert, "Trends in Automotive Communication Systems." *Proceedings of the IEEE*, Vol. 93(6), June 2005, pp. 1204-1223.

[36] Airbus. [Online]: http://www.airbus.com/en/aircraftfamilies/a350/efficiency/by_design/cockpit.html

[37] Aspen Avionics. [Online]: http://www.aspenavionics.com/index.php/products/evolutionoverview

[38] Blue Mountain Avionics. [Online]: http://www.bluemountainavionics.com/

[39] Dynon Avionics. [Online]: http://www.dynonavionics.com/

[40] Esterline CMC Electronics. [Online]: http://www.cmcelectronics.ca/En/Prodserv/Cockpit-Systems-Integration.html

[41] Garmin. [Online]: http://www.garmin.com/garmin/cms/site/us/intheair/

[42] Innovative Solutions & Support. [Online]: http://www.innovative-ss.com/

[43] J.P. Instruments. [Online]: http://www.jpinstruments.com/index.html

[44] MGL Avionics. [Online]: http://www.mglavionics.co.za/

[45] Rogerson Kratos. [Online]: http://www.rogersonkratos.com/efis.html

[46] Sandel. [Online]: http://www.sandel.com/products.php

[47] Universal Avionics. [Online]: http://www.uasc.com/products/index.asp

[48] Zodiac. [Online]: http://www.ece.zodiac.com/en/activities/flight_deck_solutions

[49] ARINC, Cockpit Display Systems (CDS) Subcommittee. [Online]: https://www.arinc.com/cf/store/catalog.cfm?prod_group_id=43&category_group_id=83

[50] ARINC 661. [Online]: http://www.aviation-ia.com/aeec/projects/cds/index.html

[51] VAPS XT, Presagis. [Online]: http://www.presagis.com/products/hmi/details/vaps_xt/

[52] Immersion. [Online]: http://www.immersion.com/products/touchscreen-feedback/1000-series.html

[53] M.B. Colton, J.M. Hollerbach, "Haptic Models of an Automotive Turn-Signal Switch: Identification and Playback Results Export Find Similar," in *Proc. EuroHaptics Conference*, World Haptics 2007, pp. 243-248, 2007.

[54] M. Enriquez, K. E. MacLean, "Impact of Haptic Warning Signal Reliability in a Time-and-Safety-Critical Task," in *Proc. International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pp. 407–414, 2004.
[55] Gulfstream. [Online]: http://www.gulfstream.com/gulfstreamevs/
[56] Kollsman. [Online]: http://www.kollsman.com/products/Sensor-Systems-Electro-Optics/enhanced-vision-system.asp
[57] Magneti Marelli, night vision system. [Online]: http://www.magnetimarelli.com/english/electronic_visione_notturna.php
[58] Magneti Marelli, traffic signal recognizing system. [Online]: http://www.magnetimarelli.com/english/electronic_rilevazione_segnaletica.php
[59] Mercedes Benz, W221 model. [Online]: http://www2.mercedes-benz.es/content/spain/mpc/mpc_spain_website/es/home_mpc/passengercars/home/new_cars/models/s-class/w221/overview/safety.0002.html
[60] Chelton Flight Systems. [Online]: http://www.cheltonflightsystems.com/Prod_cert_fea_3d_synth1.html
[61] Garmin G1000 Synthetic Vision System. [Online]: http://www8.garmin.com/pressroom/aviation/040708.html
[62] AV8OR3D, Portable Synthetic Vision for your Aircraft. [Online]: https://www.bendixking.com/AV8OR3D/default.html
[63] MetaVR. [Online]: http://www.metavr.com/technology/papers/syntheticvision.html
[64] Blusens G01 — PND GPS 3D PhotoNav [SP]. [Online]: http://www.blusens.com/en/productos/comunicaciones/g01/
[65] ARINC, Digital Flight Data Recorder (DFDR) Subcommittee. [Online]: http://www.aviation-ia.com/aeec/projects/dfdr/index.html
[66] ARINC, Flight Recorder Electronic Documentation (FRED) Subcommittee. [Online]: http://www.aviation-ia.com/aeec/projects/fred/index.html
[67] Adtron. [Online]: http://www.adtron.com/markets/
[68] Ametek. [Online]: http://www.ametekaerodefense.com/products/productcategory.cfm?ProductGroup_Id=268&ProductCategory_Id=4229&AERO_Id=2
[69] Ampex Data Systems. [Online]: http://www.ampexdata.com/index.html
[70] Ampol. [Online]: http://www.ampol-tech.com/systems/datamars104.htm
[71] Meggit Avionics. [Online]: http://www.meggitt-avionics.co.uk/staticproductlisting.asp?strareano=1051_1
[72] Seagate. [Online]: http://www.seagate.com/ww/v/index.jsp?locale=en-US&name=Military/Aerospace&vgnextoid=d5e5a35c06fb1110VgnVCM100000f5ee0a0aRCRD
[73] Signatec. [Online]: http://www.signatec.com/applications/aerospace-defense.html
[74] Silicon Systems. [Online]: http://www.siliconsystems.com/technology/technology.aspx
[75] STEC. [Online]: http://www.stec-inc.com/applications/military_aerospace.php
[76] Vanguard. [Online]: http://www.vanguard-rugged.com/rugged.html
[77] Z Microsystems. [Online]: http://www.zmicro.com/products/storage.htm
[78] ARINC, Software Data Loader (SDL) Subcommittee. [Online]: http://www.aviation-ia.com/aeec/projects/sdl/
[79] ARINC, Electronic Distribution of Software (EDS) Working Group. [Online]: http://www.aviation-ia.com/amc/projects/eds/index.html
[80] ARINC, Field Loadable Software (FLS) Working Group. [Online]: http://www.aviation-ia.com/amc/projects/fls/index.html
[81] Avionica. [Online]: http://www.avionica.com/products_gs_load615win.html
[82] Demo Systems. [Online]: http://www.demosystems.com/adl615a.php
[83] Teledine Controls. [Online]: http://www.teledyne-controls.com/productsolution/datamanagement/dataloadingsolutions.asp
[84] Fiat Ecodrive. [Online]: http://www.fiat.com/ecodrive/
[85] World Airline Entertainment Association. [Online]: http://www.waea.org/
[86] BMW Series 7 external camera. [Online]: http://www.bmw.es/es/es/newvehicles/7series/sedan/2008/allfacts/ergonomics/camera_system.html
[87] Bosch car multimedia press release. [Online]: http://www.bosch-presse.de/TBWebDB/en-US/Presstext.cfm?id=3698
[88] Thales, IFE. [Online]: https://www1.online.thalesgroup.com/col/inflight_entertainment/index.htm
[89] Panasonic, IFE. [Online]: http://www.panasonic.aero/
[90] Rockwell Collins, IFE. [Online]: http://www.rockwellcollins.com/products/cs/at/cabin-systems/single-aisle-ife/index.html
[91] Singapore Airlines, KrisWorld. [Online]: http://www.singaporeair.com/saa/en_UK/content/exp/entertainment/index.jsp
[92] Singapore Airlines Provides Linux Network PC in Every Seat. [Online]: http://blog.taragana.com/index.php/archive/singapore-airlines-provides-linux-network-pc-in-every-seat/
[93] Rockwell Collins, eTES. [Online]: http://www.rockwellcollins.com/ecat/at/eTES.html?smenu=109
[94] Rockwell Collins, dPAVES. [Online]: http://www.rockwellcollins.com/content/pdf/pdf_9925.pdf
[95] Lumexis. [Online]: http://www.lumexis.com/
[96] Emirates Airlines, IFE. [Online]: http://www.emirates.com/uk/english/flying/inflight_entertainment/inflight_entertainment.aspx
[97] Virgin America, IFE. [Online]: http://vadifference.virginamerica.com/vadiff/index.html
[98] Airvod. [Online]: http://www.airvod.com/
[99] AlsterAero. [Online]: http://www.alsteraero.de/en/system.html
[100] Avionics Innovations. [Online]: http://www.avionicsinnovations.com/pages/products.html
[101] Digecor. [Online]: http://www.digecor.com/airlines_aviation.html
[102] Flight Display Systems. [Online]: http://www.flightdisplay.com/index.php
[103] Groupe Latecoere. [Online]: http://www.latecoere.fr/eequipement_.html
[104] InFlight Entertainment Products. [Online]: http://www.ifeproducts.com/pages/products.html
[105] The IMS Company. [Online]: http://www.imsconsultants.com/index.php
[106] Intheairnet. [Online]: http://www.intheairnet.com/about.html
[107] Lefeel. [Online]: http://www.lefeel.com/html_en/APES1_1.htm
[108] PGA ELECTRONIC. [Online]: http://www.pga-avionics.com/B0310A.html
[109] Skygem. [Online]: http://www.skygemcorp.com/advance_ife.php
[110] Videon Central. [Online]: http://www.videon-central.com/inflight.php
[111] Esterline. [Online]: http://www.cmcelectronics.ca/En/Prodserv/Flight-Management-Systems-FMS.html
[112] GE Aviation. [Online]: http://www.geaviationsystems.com/Products–/Digital/Flight-Management-Systems/index.asp
[113] Honeywell, FMS. [Online]: http://www.honeywell.com/sites/aero/Flight_Management_Systems.htm
[114] Rockwell Collins, FMS. [Online]: http://www.rockwellcollins.com/products/cs/br/avionics-systems/flight_management/index.html
[115] Universal Avionics, FMS. [Online]: http://www.uasc.com/products/index.asp?contentid=prod_fms
[116] Flight Management Systems. [Online]: http://www.flightmanagementsystems.com/
[117] Tom Tom Go 920. [Online]: http://www.tomtom.com/news/category.php?ID=4&NID=394&Lid=6
[118] ARINC, Electronic Flight Bag (EFB) Interface. [Online]: http://www.aviation-ia.com/aeec/projects/efb/index.html
[119] DAC International. [Online]: http://www.dacint.com/products?item=34
[120] eFlyBook. [Online]: http://www.eflybook.com/
[121] Esterline CMC Electronics, EFB. [Online]: http://www.cmcelectronics.ca/En/Prodserv/Commav/commav_fds_efb_pilotview_en.html.html
[122] Gulfstream. [Online]: http://www.gulfstream.com/product_enhancements/planebook/
[123] NavAero. [Online]: http://www.navaero.com/index.php
[124] Teledine Controls, EFB. [Online]: http://www.teledyne-controls.com/productsolution/efb/default.asp
[125] Honeywell, EFB. [Online]: https://www.bendixking.com/AV8OR3D/AV8ORHORIZON3D/default.html
[126] F. Gil Castiñeira, D. Chaves Diéguez, F. J. González Castaño, "Integration of Nomadic Devices with Automative User Interfaces," *IEEE Transactions on Consumer Electronics*, vol. 55/1, pp. 34-41, 2009.

[127] ARINC-604. [Online]: https://www.arinc.com/cf/store/catalog_detail.cfm?item_id=350

[128] ARINC-624. [Online]: https://www.arinc.com/cf/store/catalog_detail.cfm?item_id=230

[129] Open Systems Architecture for Condition-Based Maintenance. [Online]: http://www.mimosa.org/downloads/39/index.aspx

[130] G. Bird, M. Christensen, D. Lutz, P. A. Scandura, "Use of the Integrated Vehicle Health Management in the Field of Commercial Aviation." [Online]: http://ti.arc.nasa.gov/projects/ishem/Papers/Scandura_Aviation.pdf

[131] Honeywell, VHM. [Online]: http://www51.honeywell.com/aero/technology/trends3/solutions.html

[132] Boeing 787. [Online]: http://www.aviationtoday.com/av/categories/commercial/Boeing-787-Integrations-Next-Step_932.html

[133] F. Cascio, L. Console, M. Guagliumi, M. Osella, A. Panati, S. Sottano D.T. and Dupr, "Generating on-board diagnostics of dynamic automotive systems based on qualitative models," *AI Communications*, vol. 12(1–2), pp. 33–34, 1999.

[134] S. Barone, P. D'Ambrosio and P. Erto, "A statistical monitoring approach for automotive on-board diagnostic systems," *Quality and Reliability Engineering International*, vol. 23(5), pp. 565–575, 2007.

[135] F.J. Gil-Castiñeira, F.J. González-Castaño, L. Franck, "Extending Vehicular CAN Fieldbuses With Delay-Tolerant Networks," *IEEE Transactions on Industrial Electronics*, vol. 55(9), 2008.

[136] M. Fornasa, N. Zingirian, M. Massimo Maresca, P. Baglietto, "VISIONS: a Service Oriented Architecture for Remote Vehicle Inspection," in *Proc. 2006 IEEE Intelligent Transportation Systems Conference*, ITSC 2006, Toronto, Canada, September 17-20, 2006.

[137] Airbus, Fly By Wire. [Online]: http://www.airbus.com/en/corporate/history/part_6.html

[138] D. Briere, P. Traverse, "AIRBUS A320/A330/A340 electrical flight controls - A family of fault-tolerant systems," in *Proc. Twenty-Third International Symposium on Fault-Tolerant Computing*, Tolouse, France, June 1993.

[139] Avionics Magazine: A380: 'More Electric' Aircraft. [Online]: http://www.aviationtoday.com/av/categories/commercial/12874.html

[140] P. Setlur, J. Wagner, D. Dawson and L. Powers, "A hardware-in-the-loop and virtual reality test environment for steer-by-wire system evaluations," *Proceedings of the 2003 American Control Conference*, vol.3, pp. 2584–2589, June 2003.

[141] N. Bajcinca, R. Cortesao, M. Hauschild, J- Bals and G. Hirzinger, "Haptic control for steer-by-wire systems," in *Proc. 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems*, vol. 2, pp. 2004–2009, October 2003.

[142] A. Baviskar, J.R. Wagner, D.M. Dawson, D. Braganza and P. Setlur, "An Adjustable Steer-by-Wire Haptic-Interface Tracking Controller for Ground Vehicles," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 2, pp. 546–554, 2009.

[143] Intel. [Online]l: http://www.intel.com/design/embedded/military/

[144] MIL-STD-1553B. [Online]: http://www.altadt.com/Downloads/MIL-STD-1553B & Notices.pdf

[145] Excalibur Systems. [Online]: http://www.mil-1553.com/Excalibur08/Templates/showpage.asp?DBID=1&TMID=85&FID=123

[146] Ballard Technology. [Online]: http://www.ballardtech.com/products.aspx/dir/protocol/MIL-STD-1553/

[147] Data Bus Products. [Online]: http://www.databusproducts.com/about.html

[148] Greenwood Electronic Components Limited. [Online]: http://www.greenwood-electronics.co.uk/Military_Aerospace/MIL_STD_1553BHomepage.asp

[149] ITCN. [Online]: http://www.itcninc.com/products/BCIT/BCIT-Portable_Rugged_Network_Analyzer.php

[150] National Hybrid Incorporated. [Online]: http://www.nationalhybrid.com:8080/

[151] North Hills Signal Processing. [Online]: http://www.northhills-sp.com/products-databus-dbc.html

[152] Phoenix Logistics. [Online]: http://www.phxlogistics.com/pages/databus.html

[153] Edgewater Computer Systems. [Online]: http://www.edgewater.ca/wired_1553.htm

[154] Data Device Corporation, MIL-STD-1553 Introduction to Enhanced Bit Rate 1553. [Online]: http://www.ddc-web.com/Pub/32/345.ashx

[155] ASSC, Defence Standard 00-18 Avionic Data Transmission Interface Systems Series Review. [Online]: http://assconline.co.uk/defstan0018.asp

[156] ARINC. [Online]: http://www.aviation-ia.com/aeec/projects/429/index.html

[157] SBS Avionics Technologies: ARINC 429 Commentary. [Online]: http://www.aero.polimi.it/r̃olando/bacheca/imprimatur/429commentary.pdf

[158] Condor Engineering: ARINC Protocol Tutorial. [Online]: http://digilander.libero.it/LeoDaga/Corsi/AD/Documenti/ARINCTutorial.pdf

[159] ARINC 629 Users Group. [Online]: http://www.aviation-ia.com/aeec/projects/629/index.html

[160] Aeroflex. [Online]: http://ams.aeroflex.com/ProductPages/AE_arinc629.cfm

[161] Sycos. [Online]: http://www.sycos.co.uk/629.html

[162] MilCAN Working Group. [Online]: http://www.milcan.org/

[163] Advanced Aviation Technology. [Online]: http://www.a2tech.eu/CANaerospace001.html

[164] Michael Stock Flight Systems. [Online]: http://www.stockflightsystems.com/index.php?option=com_content&task=view&id=42&Itemid=78

[165] Reiser Systemtechnik. [Online]: http://reiser-systemtechnik.de/index.php?option=com_content&task=blogcategory&id=26&Itemid=70

[166] TTCAN. [Online]: http://www.ttcan.com/Home/TTCAN/tabid/69/Default.aspx

[167] TTTech. [Online]: http://www.tttech.com/

[168] TTA-Group. [Online]: http://www.ttagroup.org/

[169] H. Bai, "Analysis of a SAE AS5643 Mil-1394b Based High-Speed Avionics Network Architecture for Space and Defense Applications," in *Proc. 2007 IEEE Aerospace Conference*, pp. 1–9, March 2007

[170] Excalibur Systems. [Online]: http://www.mil-1553.com/Templates/showpage.asp?DBID=1&TMID=86&FID=397

[171] DapTechnology. [Online]: http://www.daptechnology.com/

[172] ARINC, Network Infrastructure and Security (NIS) Subcommittee. [Online]: http://www.aviation-ia.com/aeec/projects/nis/index.html

[173] AIM. [Online]: http://www.afdx.com

[174] Sysgo. [Online]: http://www.sysgo.com/services-solutions/technology-solutions/arinc-664-afdx/

[175] Condor Engineering: AFDX Tutorial. [Online]: http://www.acalmicrosystems.co.uk/whitepapers/sbs8.pdf

[176] Alfa Romeo. [Online]: http://wwww.alfaromeo.com/

[177] Fiat. [Online]: http://www.fiat.com/

[178] Mitsubishi. [Online]: http://www.mitsubishi.com/

[179] SAAB. [Online]: http://www.saab.com/