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BILBO Network: a proposal for communications in aircraft Structural Health Monitoring sensor networks

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Abstract. In the aeronautical environment, numerous regulatory and communication protocols exist that cover interconnection of on-board equipment inside the aircraft. Developed and implemented by the airlines since the 1960s, these communication systems are reliable, strong, certified and able to contact different sensors distributed throughout the aircraft. However, the scenario is slightly different in the structural health monitoring (SHM) field as the requirements and specifications that a global SHM communication system must fulfill are distinct. The number of SHM sensors installed in the aircraft rises into the thousands, and it is impossible to maintain all of the SHM sensors in operation simultaneously because the overall power consumption would be of thousands of Watts. This design of a new communication system must consider aspects as management of the electrical power supply, topology of the network for thousands of nodes, sampling frequency for SHM analysis, data rates, selected real-time considerations, and total cable weight. The goal of the research presented in this paper is to describe and present a possible integration scheme for the large number of SHM sensors installed on-board an aircraft with low power consumption. This paper presents a new communications system for SHM sensors known as the Bi-Instruction Link Bi-Operator (BILBO).

Keywords: aeronautic; communications; electrical power supply; structural health monitoring; sensor network

1. Introduction

Maintenance of aircraft structures is a key focus for aircraft operators. The complexity of the systems involved requires extensive maintenance for all elements, including hydraulic, propulsion, electrical, avionics, and structural systems. The structural integrity is one of the most critical concerns in the airspace industry. During the fabrication process, all aeronautical elements must pass many tests and certifications carried out by aeronautics manufacturers and airworthiness authorities, i.e., the Federal Aviation Administration (2014) in the United States of America or the European Aviation Safety Agency (2014) in Europe. Furthermore, during the lifetime of an aircraft, airlines and other commercial operators of large or turbine-powered aircraft follow a continuous and detailed inspection program approved by these authorities. In a perfect scenario, all of the structures would be permanently monitored from the manufacturing process to the end of the life cycle, including the transportation, the installation, the deterioration process, and any impacts

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registered. The field that studies these technologies is known as structural health monitoring (SHM).

SHM systems have emerged to fulfill the need to exert control over the integrity of any structure over its entire lifetime (Speckmann and Henrich 2004) and to improve nondestructive testing techniques (NDT). Staszewski *et al.* (2004) presented several NDT techniques intended to ensure the structural integrity of the aircrafts. Among the most performed techniques for NDT structural inspection (e.g., visual observations, eddy current, acoustic emission, X-ray radiography), the most developed method is based on ultrasonic waves. Ultrasonic waves, also known as Lamb waves (Rose 1999), offer high sensitivity to small damages and the ability to locate nearly invisible damage. Moreover, a valuable characteristic of ultrasonic-wave-based monitoring methods is that they can be used to conduct automated SHM analysis without the need for external management. Lamb waves propagate throughout the surface and reflect multiple times at the boundaries of the structure and at any existing faults, such as cracks and delaminations, and subsequently arrive back at the transducers. The changes in both wave attenuation and wave reflection can be sensed to detect and locate damage in the material and generate alerts, maps, and reports that can be sent to external equipment, where appropriate management of the structure monitoring can be performed. As a result, maintenance and repair stops (and their costs) can be reduced to acceptable levels.

SHM systems have traditionally required expensive and bulky equipment, including interrogators, oscilloscopes, and signal generators (Bilik *et al.* 2008) (Nguyen and Rakow 2008) (Hillger 2009) (Sharif-Khodaei *et al.* 2012). Although this equipment may be valid for laboratory purposes and algorithm design, it is not feasible to install dedicated commercial ultrasonic equipment (Aranguren *et al.* 2009) on board an aircraft because of its weight, volume, and power consumption. The first low-weight/low-size prototypes were recently developed, and their on-board integration is becoming increasingly viable. For example, Phased Array Monitoring for Enhanced Life Assessment SHM (PAMELA SHM) is a fully integrated on-board electronic system that can perform in situ SHM of an aircraft's structure (Aranguren *et al.* 2009). The PAMELA SHM senses the structure using a 12-channel array of integrated phased array (PhA) transducers bonded to the structure and weighs only 400 g.

In the search for a complete self-monitoring system, the main objective of the SHM research community is the inclusion of one SHM system in each structure of an aircraft to obtain knowledge of the integrity of the complete structure of the aircraft over its entire lifetime. A representative example of the use of thousands (even dozens of thousands) of units is shown in Fig. 1. Under this scenario, two major problems are quickly noted.

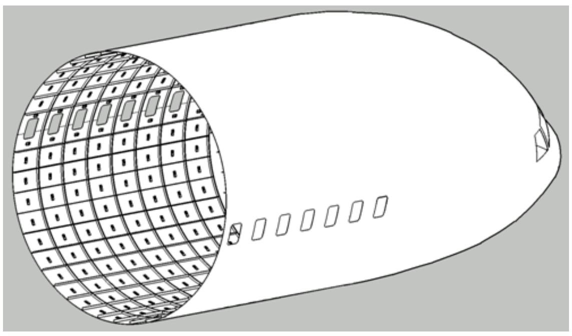

Fig. 1 On-board scenario in which many SHM sensors are installed in the aeronautical structures

A large number of SHM sensors (1000-10,000) also require a large amount of cabling to connect all of the sensors with the central computer. An efficient and reliable communication system must be adopted for this purpose. The second main issue of concern is the electrical power supply for the overall system. For example, assuming that the electrical power consumption of a single PAMELA SHM system is in the range of 15-20 W. This is an acceptable value for a laboratory setup, but it is completely unacceptable for on-board installation because the power consumption could be more than 100 kW. Both of these concerns pose important obstacles, and a solution must be found.

Therefore, the goal of the research presented in this paper is to describe and present a possible integration scheme for a large number of SHM sensors installed on-board an aircraft with overall low power consumption. The designed communication and power supply system is presented in this paper. Section 2 presents the requirements for the SHM sensor network installation and the available state-of-the-art technology. The proposed solution is discussed in Section 3. Section 4 includes an estimation of the electrical power consumption. A laboratory setup is presented in Section 5, followed by a summary and conclusions in Section 6.

2. Are on-board systems a real possibility?

This question is the topic of discussion among the airlines and scientific research community. Many challenges must be overcome to achieve on-board monitoring of the overall structure of the aircraft. In general, the large amount of structures that comprise an aircraft constrains the installation and increases the complexity of communicating efficiently among the diverse sensors and routing the generated data. The proposal for multi-SHM sensor node installation onboard an aircraft for complete structural monitoring is based on two foundations: the communication system and electronic power supply system.

2.1 Communication system

An efficient and reliable communication system must be adopted to connect a large number of SHM sensors. It would be illogical to connect these sensors in a serial configuration, because it would imply that one cable would be installed for each SHM sensor, resulting in weight increase due to the individual cables. Similarly, a single bus or a daisy-chain configuration is not a viable option because it would require the management of high data loads and any potential failure of one channel would result in a loss of communication of all endpoint sensors.

This problem has been noted by aircraft designers, and although no suitable standard exists among the existing communication systems, many of their characteristics could be useful. Classic communication systems used in modern aircrafts include Aeronautical Radio Incorporated (ARINC) 429, ARINC 629, and USD MIL-STD-1553B. These multipoint local area networks have a limitation on the maximum receivers, and their data rate is typically low (100 kbps, 2 Mbps, 1 Mbps) with a low bandwidth. Although these protocols are well established and widely implemented (e.g., ARINC 629 in the Boeing 777), their limitations make them inefficient for large-scale data transmissions. The next step in the evolution of aircraft communication system is a spin-off from the application of Ethernet-based real-time protocols that integrate commercial off-the-shelf (COTS) technologies, which make lower the cost of their implementation. For example, the Time Triggered Protocol (TTP) is a real-time communications protocol for the interconnection of modules in distributed real-time fault tolerant systems and offers data-rate speeds of up to 50 Mbps. Large numbers of nodes are connected to create a cluster that communicates over a dual-channel broadcast data bus. The ARINC 664 standard, based on switched Ethernet, is aimed specifically at civil avionic applications and replaces the aging and inadequate ARINC 429 standard for the great majority of applications. High integrity, reliability, and bandwidth are a subset of its best qualities. A deterministic implementation of ARINC 664 is represented by Avionic Full DupleX Switched Ethernet (AFDX), which is suitable for critical security applications with a limited bandwidth. The AFDX system is widely used in many current aircraft, e.g., in the Airbus A380.

Another valid option for a commutation system is wireless technology (Notay and Safdar 2011) (Hu *et al.* 2010) (Harms *et al.* 2010). These solutions are useful in aeronautical scenarios because of the considerable savings in weight and cables. Bluetooth, Zigbee, or Wi-Fi solutions can be implemented, together with wireless router nodes, where necessary, to carry information from the sensor to the end system. This approach could be useful for the transmission of information related to the structures throughout its lifetime or for the transmission of data from SHM sensors placed in inaccessible locations of the aircraft. However, wireless technologies also have important limitations, such as the power supply or range of wireless emissions among closed structures.

The described systems are designed for communication with a few endpoints, large bandwidth, and a high sampling frequency and are appropriate for critical systems. Therefore, their characteristics do not make them suitable for the SHM scenario.

2.2 Electrical power consumption system

The More Electric Aircraft (MEA) is a reality, and hydraulic, pneumatic, and mechanical systems are in the process of being replaced by their electric equivalents. The consideration of any power supply other than an electrical has no future, and the growing demand for power requirements is driven by new, diverse, and enhanced avionics systems, greater passenger comfort, and the prevalence of entertainment systems. Currently, the latest large airliner jets feature power units that deliver approximately 150 kW. Using the average power consumption values introduced in the previous section (average of 20 W of electrical consumption for a single SHM system), an overall power supply of 20,000 W would be necessary for an installation of 1000 SHM sensors. This value accounts for near 15% of the capacity of the aircraft under the most conservative scenario. The same calculation could be repeated for a scenario of 10,000 SHM sensors on-board the aircraft. In this second scenario, more than half of the power supply would be used by this non-critical system, which is clearly unacceptable.

The aircraft power system is traditionally based on a combination of 115-V/400-Hz AC for large loads and 28-V DC for avionics, flight control, and battery-driven vital services. Nevertheless, the adoption of the new generation solutions (e.g., VF, CF, VSCF) requires the use of power electronics to convert all of the motor/generator outputs into a single high-voltage DC distribution system (e.g., 270, 350, or 540 V). The use of a high value for the distribution system has the advantage of reducing the weight, size and losses while increasing the overall levels of the transmitted power. Currently, different electrical power distribution systems (EPDS) are used. Apart from such strategies as the advanced electric system (AES) or the fault-tolerant EPDS (FTEPDS), the most common is the centralized EPDS (CEPDS), a point-to-point one-center radial power distribution system. The electrical power is generated in the distribution center (typically positioned in the avionics bay) and fed individually to the different electrical loads in the aircraft.

Similar to the communication protocols, the need to run wires to each load from the same point increases the cost and volume and reduces the reliability, in addition to other drawbacks. A better alternative is the semi-distribution EPS (SDEPS), which uses a large number of power distribution centers distributed throughout the aircraft to optimize the volume, weight, cost, and reliability of the overall installation.

The viability of the SHM network requires a reduction in the electrical power consumption of the overall system and an efficient power distribution strategy.

3. BILBO Network: a new system proposal

Considering all the requirements and specifications of the system, it is concluded that indeed it is possible to install on-board an aircraft a high number of SHM sensors with acceptable levels of weight and electrical power consumption. The proposed and designed solution for an on-board multi-SHM sensor installation and communication network is known as the Bi-Instruction Link Bi-Operator (BILBO) Network and is presented in following subsections.

3.1 Network topology

The main objective of the proposed communication system is the design of a new topology for the SHM nodes of the network that allows for the inclusion of multiple distributed sensors in the aircraft. The SHM sensors are distributed in groups defined as BILBO Networks. These BILBO Networks remain connected with the central computer (CC) of the aircraft through their respective bus controllers (BC), which operate in a similar manner to that of a router, using the main communication system of the aircraft. Each BC is tasked with controlling several smaller subnetworks, referred to as BILBO Subnetworks, which include the remote SHM systems distributed throughout the aircraft. These BILBO Subnetworks are a combination of SHM endpoints connected to a shared multipoint bus. The BC manages and controls several BILBO Subnetworks independently by sampling and acquiring the SHM data and sending it to the CC. A group of BILBO Subnetworks plus the respective BC are defined as a BILBO Network. Fig. 2 illustrates a block diagram of this proposed scenario.

Not all of the BILBO Networks contain the same number of BILBO Subnetworks. In certain locations, the topology and distribution in the aircraft may differ as a function of size. The capabilities of the BC allow them to manage a dozen different Subnetworks, but this is not a fixed number.

Additionally, not all of the BILBO Subnetworks contain the same number of SHM nodes. The number of these nodes or SHM Endpoints connected to the shared bus is variable and limited to approximately 50. One BILBO Network is presented in Fig. 3.

As stated, two elements are included in the network: the SHM Endpoints and the Bus Controllers. The first element is based on two operators with interconnected modules that share access to the communication line and electrical supply. These two operators, known as the activity watchdog module (AWM) and the SHM Sensor, are represented in Fig. 4. A communication driver and power module are also included. The AWM is based on an ultra-low-power microcontroller whose main functions consist of communicating with the BC and switching the power module of the SHM Sensor. The SHM Sensor, which is based on a field-programmable gate array (FPGA), performs the specific functions and process of SHM analysis. This bi-operator structure will be essential for an efficient electrical power consumption system, as will be explained in the following subsection.

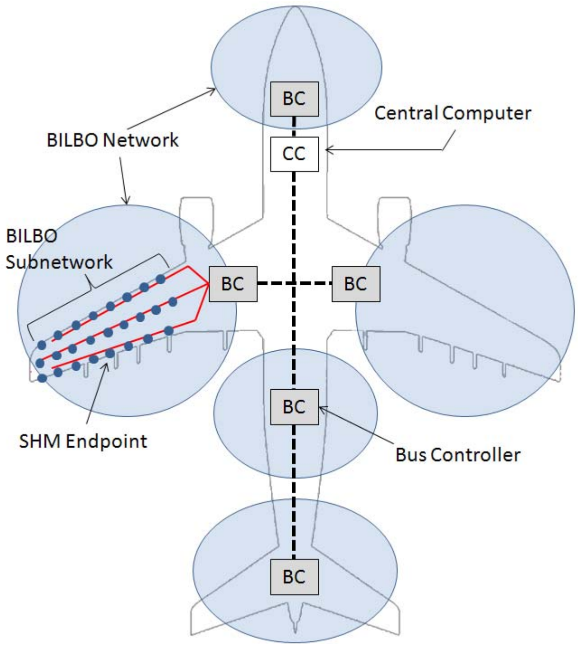

Fig. 2 Representation of a BILBO Network installation on-board an aircraft. The SHM Endpoints are contained in BILBO Subnetworks, which are gathered in BILBO Networks. Bus Controllers connect the BILBO Networks with the Central Computer using the main communication system of the aircraft

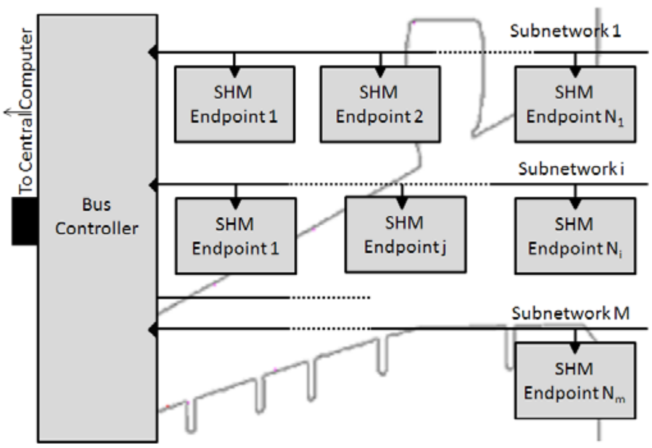

Fig. 3 Representation of a BILBO Network composed of a Bus Controller and many BILBO Subnetworks, which contain multiple SHM Endpoints

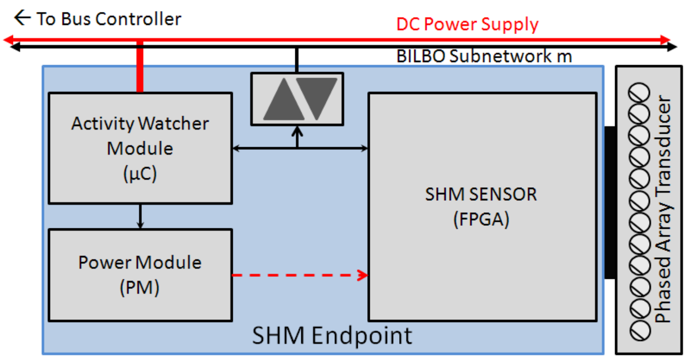

Fig. 4 Bi-operator architecture of the SHM Endpoint

The architecture of the BC, which is a key element in this system, is presented in Fig. 5. The BC controls several BILBO Subnetworks and provides them with power. The main operator of the Bus Controller is a FPGA, which communicates individually and independently with the respective SHM Endpoints of its BILBO Subnetworks. Moreover, the BC has the ability to provide or remove the electrical power supplied to its BILBO Subnetworks, similar to a distributed power system.

A first approach in the search for the perfect SHM system suggests that one SHM Endpoint should be installed in each structure of the aircraft, independent of the size, shape, and location of that structure. Evidently, the viability of this scenario can be rejected due to its high cost. A more realistic approach might consist of installing the sensors in the most sensitive and critical areas of the plane, i.e., the leading edge rib in the wings of the aircraft. These are the locations where de-bonding, cracking, and impacts are more prone to occur, and they are also the most difficult to access for visual inspection.

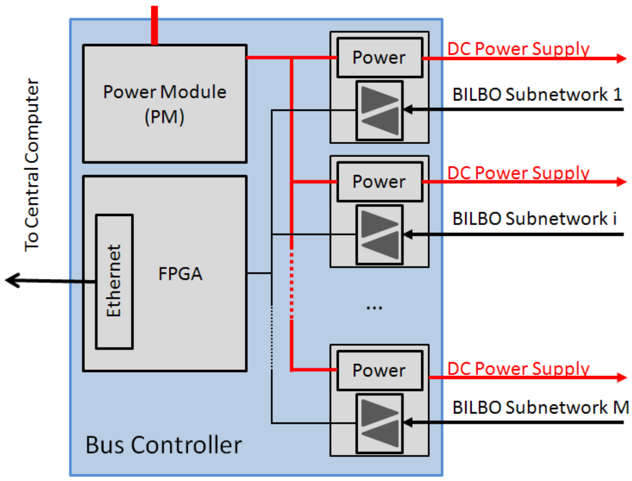

Fig. 5 Architecture of the Bus Controller

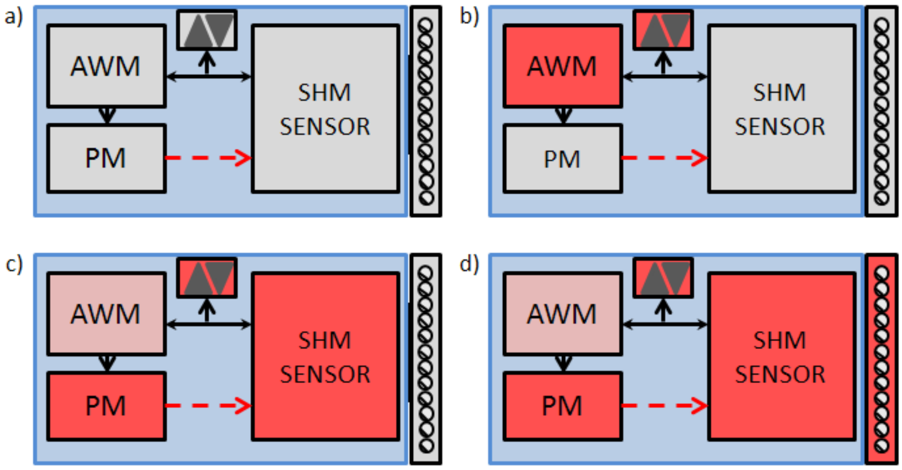

Fig. 6 Four power modes available in the SHM setup: (a) NET_OFF_MODE, (b) SLEEP_MODE, (c) ACTIVE_MODE and (d) TESTING_MODE

3.2 Power modes

As previously stated, the primary objective of this design is to reduce the global electrical power consumption of the SHM Endpoint installation. Using selective powering among the BILBO Subnetworks, only one subnetwork of sensors can operate in a fixed moment, whereas the remainder of the subnetworks (the great majority of the SHM Endpoints in the aircraft) will be completely switched off, and their consumption will be zero, as managed by the respective Bus Controllers. However, will this approach be sufficient?

The Bus Controllers are always activated and in operation, either waiting for orders from the CC through the primary aircraft network or communicating with the final SHM Endpoints. However, their power consumption is acceptable and represents a fixed but low level of the total consumption of the aircraft. The decisive factor lies in the remainder of the equipment.

In the scenario in which one BILBO Subnetwork contains approximately 50 nodes, the power consumption of the subnetwork will reach 1000 W if only one SHM node operates and sends data while the remainder of the nodes wait their turn. The total power consumption would be quite high. To reduce the power consumption, every SHM Endpoint is constructed using the Bi-Operator architecture. This structure allows the complete SHM Endpoint to operate in different power modes depending on which operators are on and off. The Bus Controllers are activated at every moment, have fixed power consumptions, and are able to switch on and off of their respective BILBO Subnetworks. This capacity and the bi-operator structure require four power modes, as represented in Fig. 6.

The first mode (NET_OFF_MODE or NM) represents the state of the SHM system in which its BILBO Subnetwork is switched off. Without any electrical power, the endpoint will also be set to off, and its power consumption will be non-existent. The situation will be different if the BC decides to switch on one of its BILBO Subnetworks. In that moment, all of the endpoints of the subnetwork will receive a power supply and will automatically shift to the second mode

(SLEEP_MODE or SM). In this second power mode, only the AWM will be switched on, while de SHM Sensor will remain switched off. The consumption of the AWM is less than 100 mW, and a large portion of this consumption is due to the communication driver. In total, the power consumption related to this Subnetwork will be approximately 5 W, which is an acceptable level.

If the BC orders a certain endpoint to acquire data, the AWM activates the power module, which switches on the second operator, the SHM Sensor. At this time, the power consumption will rise to approximately 5-15 W, whereas the remainder of the nodes of the Subnetwork will remain in SM. The endpoint will be active in this third power mode (ACTIVE_MODE or AM) during the communication process. However, another scenario exists in which the power consumption is higher. When the SHM Sensor performs the SHM duties (e.g., excitation and acquisition of the piezoelectric transducers, data conversion), the power consumption will suddenly rise to 20-30 W because new electronic components of the equipment (piezoelectric transducers, phased arrays, ADC, DAC, etc.) will be in operation. This fourth power mode (TESTING_MODE or TM) represents the highest power consumption of all modes, although it is the most brief in duration.

3.3 Communication protocol

The bi-operator architecture is designed for selective switching of on-off conditions in the communication protocol. In the BILBO Network, two different protocols can operate under the same cabling. Each protocol is understood by one operator and ignored by the other. In a transaction, both the BC and SHM Endpoint can operate using two different protocols at separate times. The two instruction links are control link (CL) and data link (DL). Although both modes may share certain characteristics, there are clear differences between each mode. A Bus Controller and the bi-operator SHM endpoint system architecture are represented from a communication protocol point of view in Fig. 7.

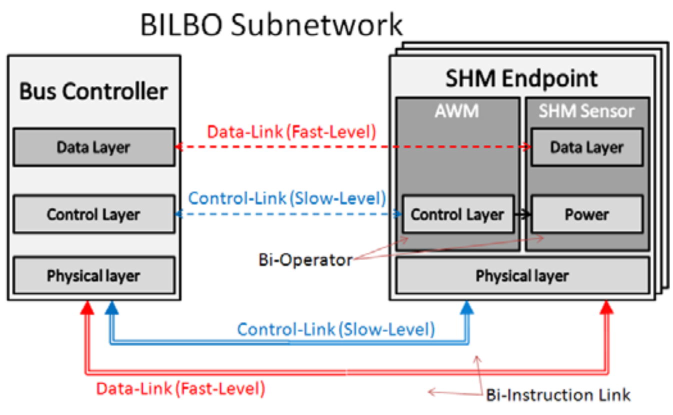

Fig. 7 Point-to-point communication protocol between the Bus Controller (left) and the SHM Endpoint systems (right)

To ensure efficient sharing of the multipoint bus and to avoid a situation in which more than one SHM Endpoint might send information at the same time, this system follows a master-slave approach. In this case, the BC has unidirectional control over the remainder of the devices in the bus. The BC is tasked with ordering a SHM Endpoint to start/stop working, and the SHM Endpoint has permission to send data to the bus only in that moment. Otherwise, all of the devices will wait for new orders.

The AWM exchanges control data with the BC under the Control Link. This communication protocol is supported by a low-consumption microcontroller. This communication device is byte oriented and shares many characteristics with the low data-real serial protocols (ARINC 429, USD MIL-STD-1553B, etc.). The reason for this choice is that the AWM is an ultra-low power consumption microcontroller that manages low-data-rate communications. Data transfer in this operating mode will be slow but will not present a problem because the exchanged payload is low. Moreover, because the electrical power consumption in SLEEP_MODE is quite low, the time during which this operator remains in this power mode will not have a significant impact on the power consumption.

The data operator is tasked with transmitting higher data loads. A SHM sensor can typically generate different results, from a single alarm report (signaling that everything is fine or that no changes have been detected) to a high-load SHM analysis in the form of an image, which typically requires more than 1 MB. In this case, it is essential to complete the transmission as soon as possible because the electrical power consumption in AM is high and has a negative impact on the overall power consumption. For this task, the communication protocol must manage high data loads and will use a payload orientation instead of a serial orientation.

However, although these payload-orientated protocols transfer data with high speed, they typically suffer from low efficiency. These protocols are not actually sending data during the entire time that it takes to complete a data transfer. In this scenario, this problem must be solved, and an output transfer rate of 100% must be achieved to finish the transmission as soon as possible such that the SHM sensor can switch off and return to SM. This practice is similar to that implemented in all computers in the world and is known as direct access memory (DMA). This feature allows the hardware subsystems of the computer to transfer or receive data from the memory independent of the central processing unit (CPU), saving time and resources from the CPU. Using this data-flow processing instead of a sequential flow utilizes the concurrent capacities of the FPGA and accelerates the transmission of data between endpoints.

The Bus Controller must share certain characteristics of the SHM Endpoints and must not only have the ability to switch each of its subnetworks on and off but also to understand and manage both communication links. Because the BC does not need to maintain a low power consumption status, its architecture is based on an operator or FPGA, which will manage both links multiplexed under the same implementation in all ports of its respective BILBO Subnetworks bus connections.

4. BILBO operation

Next, the power consumption and sampling frequency of the BILBO Network are estimated considering the previous considerations. In a real environment, many factors influence the result, but the main factor is the number of SHM Endpoints that must be monitored. This number will depend on the size of the aircraft or the sensitive areas that will be analyzed. More or fewer BILBO Networks and Subnetworks will be required as a function of this number.

4.1 Single SHM Endpoint operation

As a first approach to the SHM installation, we assume that at every moment, only one of the SHM Endpoints will perform an SHM analysis out of the overall SHM node installations and will thus operate in TESTING_MODE. Under this scenario, equation (1) presents a formula used to calculate the total power consumption P_{TOT} of the BILBO Network installation, where P_{BC} is the fixed electrical power consumption of the Bus Controller, P_{SM} is the electrical power consumption of the SHM Endpoint in SLEEP_MODE (SM), and P_{TM} represents the power consumption of the SHM Endpoint in TESTING_MODE (TM). In this case, the consumption of AM has been discarded because TM is slightly superior. Also, N represents the number of SHM Endpoints of the BILBO Subnetwork undergoing analysis, and Q represents the number of BILBO Networks and therefore the number of BC in the aircraft.

$$P_{TOT} = \sum_{Q} P_{BC} + \sum_{N-1} P_{SM} + P_{TM} \tag{1}$$

4.2 Multiple SHM Endpoint operation

An SHM analysis (excitation, acquisition, processing, and data transmission) performed using an optimal SHM system may have a duration of 3 s. Thus, for a 1000-SHM unit installation, a sequential sampling of all of the systems will be possible within one hour. However, it will be necessary to perform several SHM analyses concurrently if a higher sampling frequency is desired or if there are additional SHM Endpoints installed. In that case, more than one SHM Endpoint will be operating at the same time. Therefore, the electrical power consumption will be higher. Another example of this scenario occurs when using the pitch-catch technique. This technique can be used to excite the structure through one SHM Endpoint while the others sense the structural response, performing combined and synchronized tests. This approach is useful for the inspection of rivet lines, structural unions, stiffener de-bonding, analysis of larger-dimension structures, and soldered junctions. In all of these cases, two or more sensors may operate simultaneously, thus increasing the total power consumption.

In these cases, the estimated power can be calculated using Eq. (2), where i is the number of SHM sensors of the different Subnetworks activated and j is the number of BILBO subnetworks operating simultaneously.

$$P_{TOT} = \sum_{Q} P_{BC} + \left(\sum_{N-i} P_{SM} + \sum_{i} P_{TM} \right) * j \tag{2}$$

4.3 Power estimation

By applying equations (1) and (2), it is possible to obtain an approximate estimation of the overall power consumption, as presented in Table 1. For these particular calculations, the following estimation values were adopted based on the performance of the PAMELA SHM: P_{BC} is 35 W, P_{SM} is 0.5 W, and P_{TM} is 20 W, the maximum number of SHM Endpoints is limited to 50, and the number of BILBO Subnetworks controlled by the BC is eight. Assuming that an SHM endpoint takes 3 s to sense and send the SHM data, the estimated times are presented in Table 1.

Table 1 Configurable Characteristics of the Excitation Signal

	Consumption (W)	
Test Frequency	1000 SHM Sensors	10,000 SHM Sensors
60 min.	150	1430
30 min.	170	1980
15 min.	190	3080

In the presented calculations, the largest portion of the electrical power consumption is due to the BC equipments. Their number will depend on how the SHM Endpoints will remain distributed and in how many BILBO Networks.

The dates in Table 1 indicate that is possible to install 1000 sensors in an aircraft with the proposed communication system and sample them every 15 min with an overall electric power consumption of 200 W.

5. Laboratory setup

The proposed and designed BILBO Network was developed and tested in a laboratory environment, and the power consumption levels and selective switching of both operators of each SHM Endpoint were investigated. A schematic of the laboratory setup is included in Fig. 8.

The Bi-instruction Link protocol and the Bi-Operator architecture are based on the use of two different communication strategies, as designed. Apart from the general considerations previously presented, there are certain other characteristics of the BILBO Network communication system that are explained in the current section.

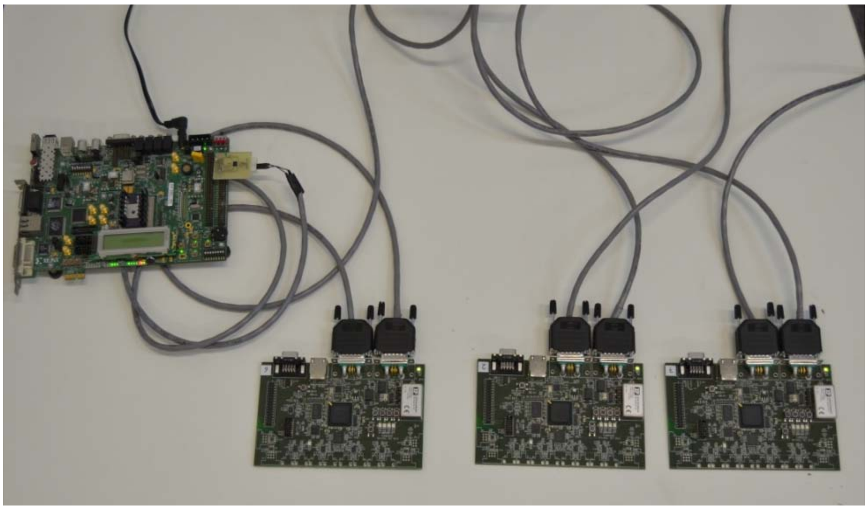

Fig. 8 Laboratory setup of a BILBO Subnetwork

As stated, the AWM of the SHM Endpoint consists of an ultra-low microcontroller of the nano-Watt XLP Technology family from Microchip, and a FPGA from Xilinx's Spartan-6 family. The other main module of this board is a communication driver from the HVD family of Texas Instruments. This receiver for industrial applications connects to a half-duplex (two-wire bus) and has a data rate of up to 50 Mbps. This driver allows over 200 nodes to remain connected to the bus. Its power consumption, though higher than that of the microcontroller, is less than 100 mW. In addition to the DC/DC switches and voltage regulators, these three are the main modules of a SHM terminal chosen with power consumption savings in mind. The Bus Controller is based on a Virtex-5 FPGA from Xilinx with the respective conditioning hardware necessary to adapt it to the BILBO Subnetwork.

Another characteristic that allows for equilibrated electrical power consumption and high immunity to interference is differential signaling. The cabling of the BILBO bus is composed of a differential pair of wires (D+ and D-) and two wires for the electrical power supply (Vcc and Gnd). This design is similar to the USB cabling, although the voltage of the power supply is higher in this case, thus reducing the current. An image of the cable cross-section is presented in Fig. 9.

Another characteristic of the installation and physical medium is the connector for each SHM Endpoint. In the particular case of this laboratory setup, the chosen coupling terminals are represented in Fig. 10. The system includes a switch, which is always closed by default, and the communication line is extended from one end to the other.

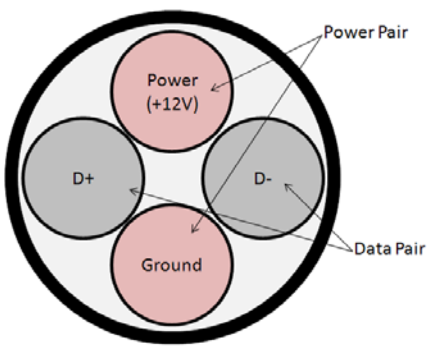

Fig. 9 BILBO Network bus cable cross-section

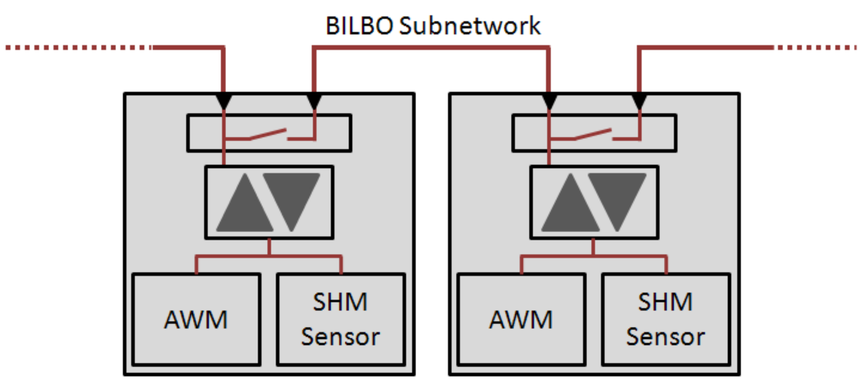

Fig. 10 SHM Endpoints power connections to the BILBO Subnetwork bus

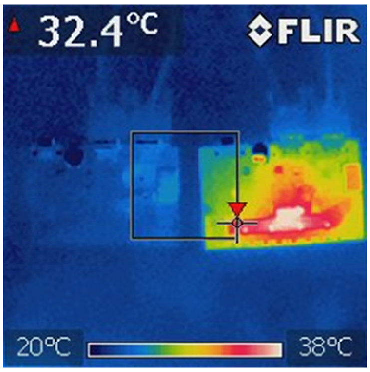

Fig. 11 Thermal performance of two SHM Endpoints. The left SHM Endpoint only has the AWM activated while the right SHM Endpoint has both the AWM and the SHM Sensor activated

The approach for these multipoint bus connections is described as follows. During the first start-up of the system, the BC assigns the identification numbers that receive each SHM Endpoint of the BILBO Subnetwork individually. Initially, none of the SHM Endpoints have a pre-configured number. This inauguration process is performed sequentially instead of as a broadcast message. After a new SHM Endpoint has been configured, the SHM node will have the capacity to extend the communication to the next node to be configured. This process will be repeated sequentially until the last system of the BILBO Subnetwork has been configured. In the case in which failure of one SHM Sensor endangers the entire subnetwork, the switch will operate as a short-circuit to bypass the communication.

The communication payloads of both links of the communication are different. The low-data-rate serial communications in the CL are byte oriented because the payload for transfer is typically low, i.e., less than 10 bytes. Checksum fields are included for error control. This communication can be implemented easily using the low-power consumption microcontroller of the AWM. However, the payloads are different than those transmitted in DL communications. This strategy, which is datagram oriented, handles more data than the FPGA or the BC can send/receive at once. Data recovery will penalize the system both in time and consumption. Therefore, the overall payload (up to 1 MB) will be fragmented and re-assembled in small datagrams, and cyclic redundancy check (CRC) fields will be added.

The data rates for the two instruction links are also quite different. The chosen rates are 115,200 bytes/s and 10 Mb/s. The data link data rate is 100 times faster than the control link data. The first data rate is fully understood using a basic microcontroller, and the second data rate can be developed with 100% performance by a FPGA.

The difference between the CL and DL messages is significant, and their codification and frequencies are different. Therefore, the AWM operator neither decodes nor understands the data messages exchanged by the SHM Sensor and BC and vice versa. The messages that are not addressed to these devices are treated as noise.

Another practice is the use of Manchester coding techniques for the data. The DL uses Manchester coding with the data signal and clock signal multiplexed in the same line. The clock signal can be recovered from the encoded data during reception. Moreover, the encoding of each data bit has at least one transition and occupies the same time period. This characteristic ensures that there is no DC component in the line and that it will have equilibrated the foreseeable electrical power consumption independently of the data transmitted.

In the laboratory setup, each SHM Subnetwork has approximately 50 SHM endpoints. This number is not chosen at random but was chosen as a function of the power consumption, the time conditions, and the thickness of the cabling, in addition to such other considerations as the fan-out (degradation of the power supply signal over a long bus of nodes). Not every BILBO Subnetwork works with the same number of nodes.

Finally, the power mode transitions and electrical power consumption of this bi-operator structure were studied and validated. Fig. 11 includes an interesting insight into the two main power modes of the SHM Endpoint thermal performance. This photograph was acquired with an infrared or thermography camera.

In the figure, the differences between these two power modes are clearly shown. The SHM Endpoint placed to the left, which is working in SLEEP _MODE, only has the Activity Watchdog Module activated and therefore the greatest part of the printed circuit board (PCB) is switched off. This power mode does not have an impact in the power consumption. The warmest point of this SHM Endpoint rises to 27ºC. On the other hand, the SHM Endpoint to the right is working in ACTIVE_MODE with both the SHM Sensor and the AWM activated and working at full performance, which is clearly appreciated in the brightest and warmest colors captured in the photograph. The hottest spot in this PCB rises to 47ºC. The difference between both power modes is definitely observed and a reduction in the power consumption required is achieved. The procedure, architecture and design are validated.

6. Conclusions

Maintenance of aircraft structures is a key aspect for aircraft operators, and the SHM field offers new solutions for the on-board inspection of aircraft structures. However, the viability of global installation of multiple SHM sensors in an aircraft faces two major setbacks: the electrical power consumption and the communication network and associated protocols. The electrical power supply demand for a large number of distributed SHM sensors poses a key obstacle, and a new strategy should be adopted if this installation is desired. The Bi-Instruction Link Bi-Operator (BILBO) Network is a proposed system for the interconnection of multiple SHM sensors inside an aircraft.

- The BILBO Network is based on a dual architecture of the SHM nodes. Every endpoint is composed of two operators such that selective switching on and off allows for the reduction of the electrical consumption to an acceptable ultra-low level.
- This architecture conditions the communication protocols, which also have been defined following a dual configuration. Communication is based on two links, the Control Link and Data Link, which alternate their actuations as a function of which operators are activated at each moment.
- As a function of the size and shape of the aircraft, the SHM Endpoints are gathered in different BILBO Subnetworks using a multipoint bus configuration and are controlled by a Bus Controller. The Bus Controller operates as a master device able to manage several BILBO Subnetworks, conforming to a greater BILBO Network.
- The Bus Controllers switch on, communicate with, and switch off the SHM Endpoints and subsequently send the received information to the Central Computer.

- The electrical power consumption of the overall system has been estimated. With this BILBO Network architecture, 1000 on-board SHM sensor installations and a sampling frequency of 15 min, it is possible to operate with a power supply of 150-200 W. It would also be possible to power up 10,000 SHM sensors using less than 2000-3000 W in the same period of time.

A laboratory prototype has been designed, built, and installed to validate this strategy and this architecture. BILBO Network has been tested and validated.

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