PROJECT FINAL REPORT

Grant Agreement number: 323466

Project acronym: WILDCRAFT

Project title: Wireless Smart Distributed End System for Aircraft

Funding Scheme: Clean Sky

Period covered: from 1st October 2012 to 31st May 2014

Name of the scientific representative of the project's co-ordinator[1], Title and Organisation:

Andoni Irizar

Department of Electronic & Communications

CEIT

Paseo Manuel Lardizabal 15, 20018, San Sebastián, Spain

Tel: (+34) 943 212800

Fax: (+34) 943 213076

E-mail: airizar@ceit.es

Project website address: http://www.wildcraft-eu.org/

The WILDCRAFT project was funded by the European Commission under CleanSky Joint Technology Initiative for Aeronautics and Air Transport

[1] Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement.

4.1 Final publishable summary report

List of Beneficiaries

Beneficiary Number	Beneficiary name	Beneficiary short name	Country	Date enter project	Date exit project
1 (Coordinator)	Centro de Estudios e Investigaciones Técnicas	CEIT	Spain	1	20
2	Integrasys	INTE	Spain	1	20

Contact details

Dr Andoni Irizar
CEIT
Paseo Manuel de Lardizabal, 15
20018 San Sebastian (Spain)
Tel. (+34) 943212800
Fax: (+34) 943213076
Email: airizar@ceit.es

Summary description of project objectives

WILDCRAFT proposes the design, development and testing of a proof-of-concept demonstrator of a Wireless Sensor Network (WSN) aimed at applications in the aerospace industry. The continuous pressure on aircraft manufacturers to produce better and more secure aircrafts has led to increasing costs in maintenance and monitoring procedures that are being performed at given time intervals to assess the state of an aircraft. Wireless Sensor Networks (WSN) allows the continuous monitoring of critical variables of the operation of an aircraft, and as such they are able to issue early warning of a possible problem for immediate repairing.

WILDCRAFT is paying attention to data fusion techniques needed for obtaining an "abstract sensor" from the measurements taken by a multiplicity of sensors deployed in a specific part in an aircraft. To that end we are going to study the most suitable algorithms to infer, estimate or summarize the state of the physical variable being measured. The designed algorithms will be implemented in a FPGA platform. In WILDCRAFT we are also considering the safety critical nature of any on-board system in an aircraft.

The set of safety requirements of the system will be compiled and used for the specification, design and development of the building blocks of the system: sensors, energy harvesting, RF transceiver and microprocessor, and the corresponding levels of software and programmable hardware blocks.

Objectives

The project's objectives are:

- To define an architecture for a WSN able to operate in an aircraft environment. Among the characteristics we are seeking for the WSN are:
    - Range of communications between nodes must be at least the size of a typical aircraft.
    - Worldwide deployment of the system. This is particularly important if RF communications are used.
    - Flexible architecture that allows the installation of different kind of sensors with minimal changes (preferably, software changes)
    - The definition of the architecture must take into account functional specifications applicable to the aerospace industry with regard to weight, RF emissions and power consumption.
    - Low Power Consumption. Evaluate the impact of energy harvesting and power management in the total power consumption of the nodes.
- To take into account the Safety Critical specifications imposed by the aerospace industry in the design of such a system. A risk assessment will be made to confront possible problems at all level of the device life cycle: design, validation and operation.
- To develop a demonstrator of the WSN using several sensors nodes (temperature, strain gauges, vibrations) and one global computation unit that will gather and process the data obtained from the sensors in order to show the state of the aircraft's parts by presenting them in a unified way.
- The final objective of WILDCRAFT is to serve as a fully automated way of inspecting the state of an aircraft structure and to achieve that it will be necessary to process a large amount of data in an intelligent way. WILDCRAFT will be using the inherent redundancy of WSNs to augment the overall fault tolerance of the system by employing data fusion techniques that can be implemented both at the node level and also at a global level to produce values that can be thought as a measure from an "abstract sensor" that represent the measures from all de WSN.

Work performed and main results achieved

After the study and analysis of the functional requirement of the system regarding data rate, number of sensor nodes and type of sensors, frequency bands, power consumption and reliability issues, we have reached the following design decisions for the different parts of the WILDCRAFT system.

- **Sensor Node Architecture.** The central component of the node is the MSP430 microprocessor that will manage and monitor all the functionality provided by the node: sensoring, power management and wireless communications. The hardware and software architectures are given in Figure 1 and Figure 3 respectively. Moreover an estimated budget of the components to be used in the sensor node is provided for reference only (the prices are usually being quoted for small quantities).
    - **Sensors**. The components selected for acceleration, temperature and humidity present a complete solution from the sensor itself, to the signal conditioning, analog-to-digital conversion and digital interfacing. An integrated solution that saves board space, simplifies PCB layout and routing while providing a very good resolution and variation ranges for the given quantity, very good power consumption behaviour and sampling rates can be programmed from the microcontroller. There is no integrated solution for the strain gauge sensors that measure deformations. An IC (MAX1452) has been selected for conditioning the output signals of the Wheastone Bridge. This IC is an analog circuit that has a programmable amplifier and several offset compensation blocks that can be controlled digitally from a microcontroller. The analog-to-digital of the strain gauge signal conversion will be made on the microcontroller's ADC. The sampling frequency has been estimated as near to 100-200 Hz taking into account the typical modes of vibration in aircraft's structures.

    - **Energy Harvesting.** We have selected a thermal harvester as the source of additional energy in our system. Given the environmental conditions in which the system will operate we think that this source is the most readily available. The harvester circuitry has been designed to include the step-up converter and the battery charger. Power supply status indicators have also been included to measure the power provided by the harvester, battery fuel gauges and the power consumption of the sensor node.

    - **Programming & Testing Circuitry.** A serial interface and a JTAG connector have been added to the sensor node for testing and debugging purposes. Additionally we have included current sense circuitry to measure the power consumption of the sensor node under different modes of operation. The current sense is an analog circuit that is sampled by the A/D converter of the microcontroller.

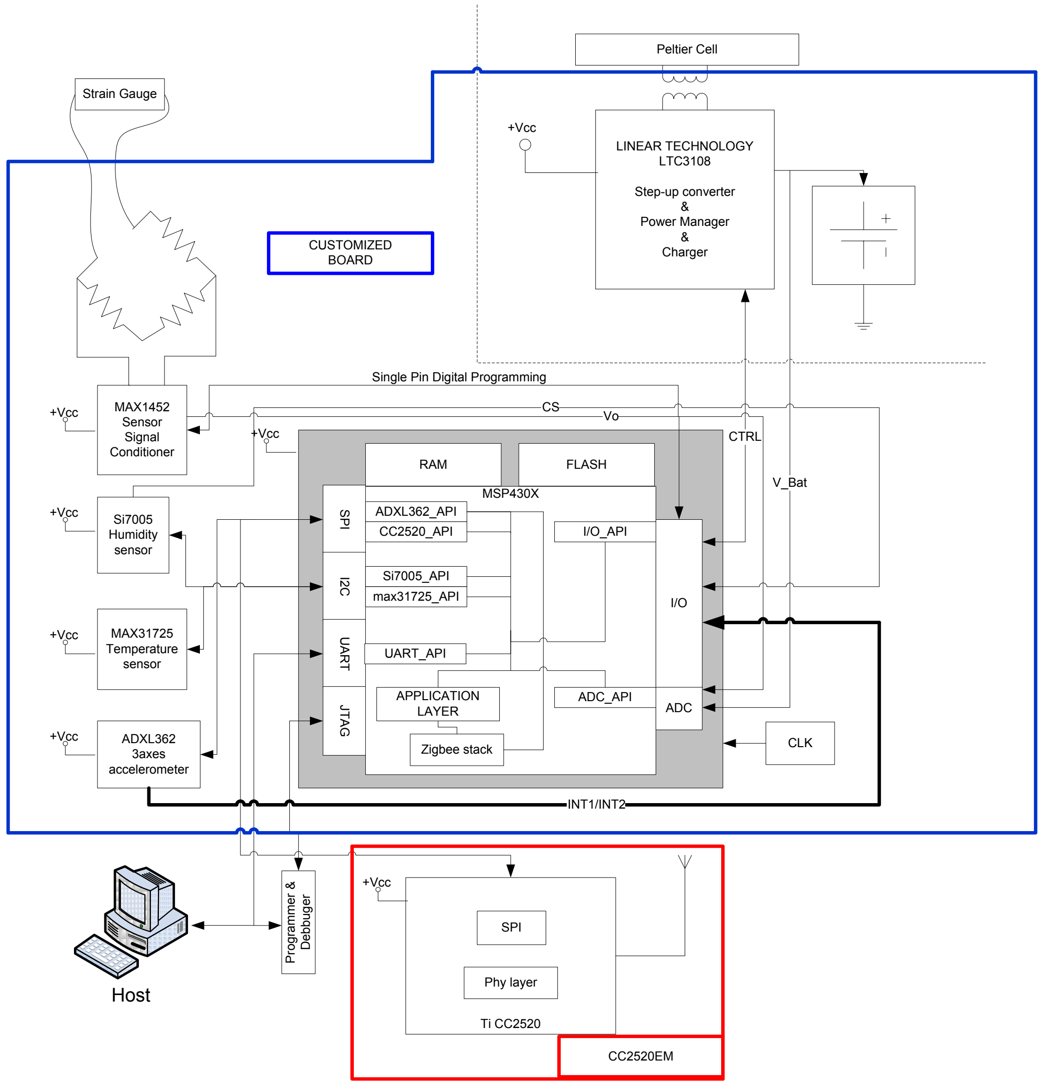

Figure 1: Hardware Architecture of the Sensor Node

- **Global Node Architecture.** The architecture of the global node has been divided into a coordinating node that has direct access to the Tx/Rx of the WSN and a computation node for post-processing the data obtained from the sensors. The block diagram is given in Figure 2. The main processor is an IMX51 Cortex-A8 ARM processor from Freescale. This device will hold a Linux OS that provides support for external devices like USB and micro-USB, SD card and ethernet connectivity. The processor interfaces with two elements of the global node: the

WSN coordination node (see below) vi a SPI interface and the global computation element in a Spartan6 FPGA using the EIM (Extension Interface Module)

- **WSN Coordination Node.** Its architecture is the same as other sensor node. The functionality is, of course, different providing network coordination and keeping synchronization with the rest of the sensor nodes. Their main task is to gather the data from the different sensors. The coordinating node has a SPI interface with the main processor (see next)
- **Global Computation.** The computation node consists of an ARM processor (iMX51 @ 800MHz) and a FPGA (Spartan6 LX9) for hardware acceleration. The ARM processor obtains the data from the sensors via a SPI interface. Although the ARM device is capable of fast processing large amounts of data, the FPGA is serving for accelerating certain very demanding tasks. In our system the FPGA is currently performing two types of operations: a 1024-point FFT and 512-points cross-correlations.
  - The processor handles the operation of the FPGA via a special memory interface that access to registers inside the FPGA to inform about the tasks that must be performed. That interface between processor and FPGA is made using very simple C code, so the operations in the FPGA are very transparent from the user point o view.

- **Communications/Topology/Network Operation.** The architecture of the wireless communication interface is based on the 802.15.4 standard in the 2.4GHz band. The chipsets that will be used in the sensor node are the CC2520 Transceiver and the MSP430 microcontroller, both from Texas Instrument. We have selected a dual-chip solution instead of a SoC solution because we wanted to have flexibility in the peripherals needed for the sensor, processing power and internal memory that a microcontroller has, as opposed to a single-chip solution that offers very limited performance. The network topology selected is a star-tree topology where each node communicates directly or through router nodes with the global node. The operation of the sensor network is such that each node obtains the measures from the sensors at the same time, but the data transmission is made sequentially one node at a time, so the whole bandwidth is available for the nodes, without additional interferences from other nodes. A node synchronization strategy must be followed in order to ensure the time-coherence of the data obtained from the sensors and the time-division operation of the wireless media.
  - **Power Consumption and Battery Operation of the Sensor Nodes.**

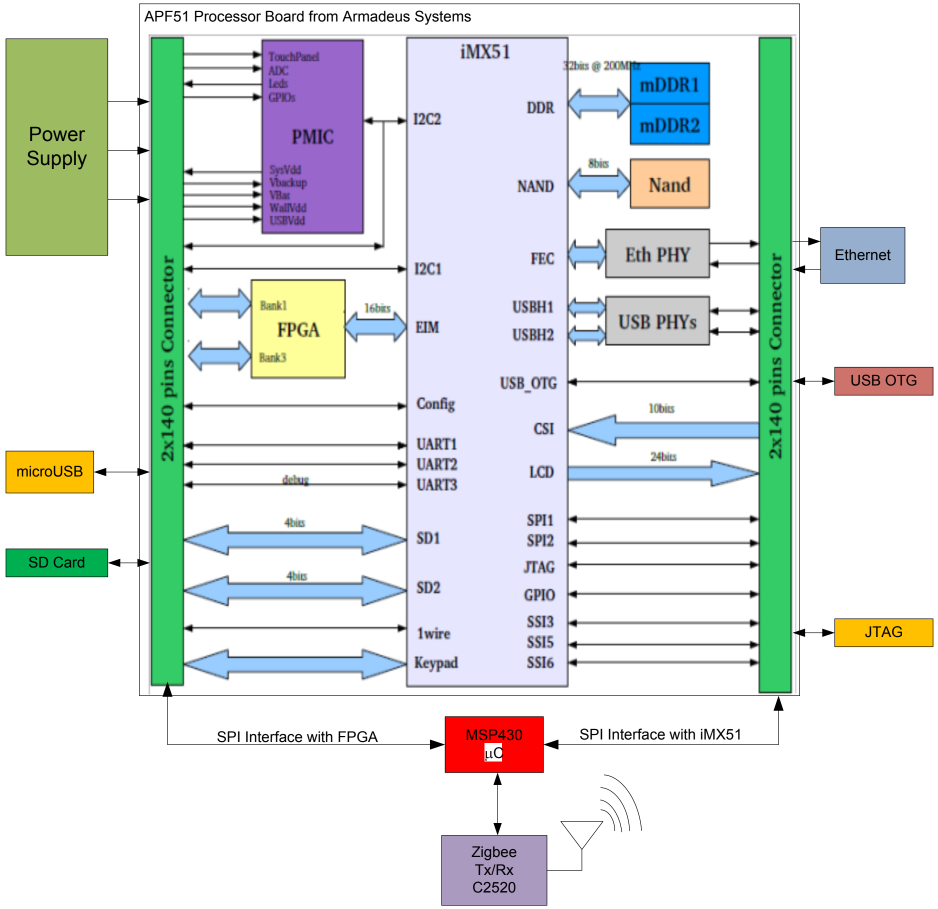

Figure 2: Global Node Hardware Architecture

- **Software Architecture.** The proposed architecture is based on a multi-layered architecture with different software components. Low-level components (middleware) execute basic tasks, while higher level components use the API offered by the middleware to achieve more complicated functionality while maintaining efficiency and simplicity of coding. The basic functionality of our middleware system is to hide the low-level details of the sensor node (e.g. manage the system resources efficiently) by providing a clear interface to applications developed at the highest level.
    - **WSN Nodes.**
        - **Sensor Nodes**

- Coordination Node

- Global Computation Processor.

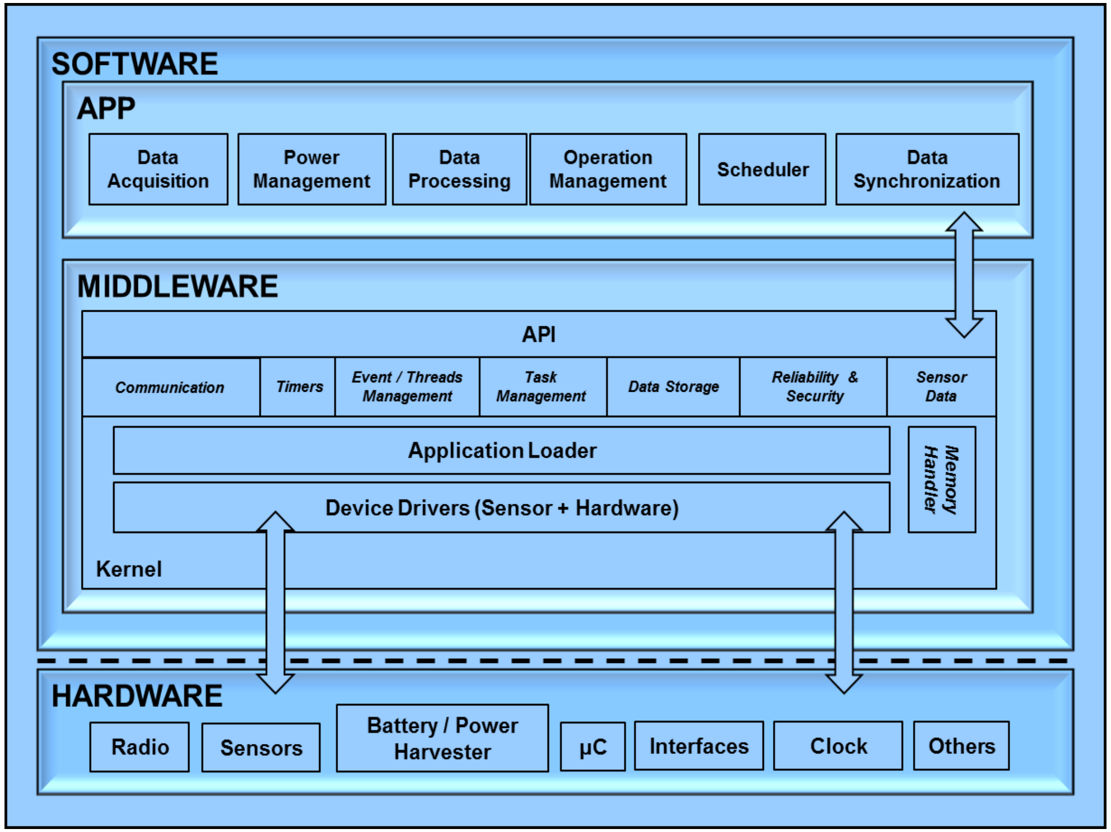

Figure 3: Software Architecture of the Sensor Node

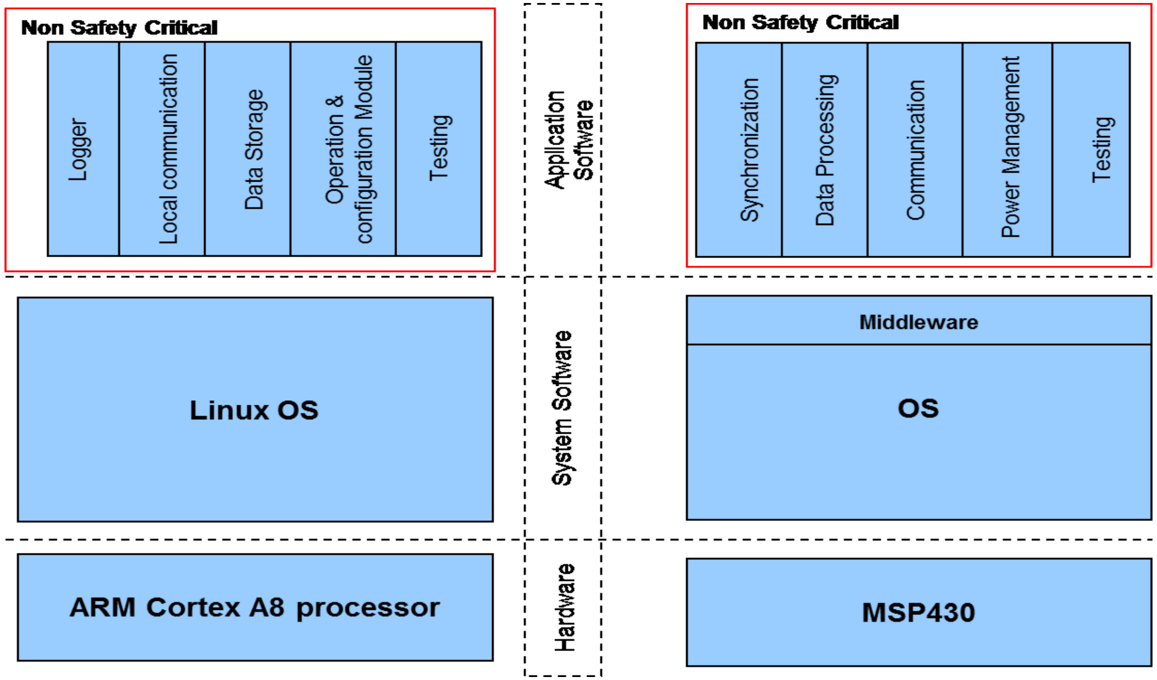

Figure 4: Global Node Software Architecture

- **Testing and validation of the WSN**

Based on these design decisions we have obtained the following results:

- A WSN consisting of several nodes. The WSN was demonstrated to work in a aircraft environment
  - Work under different Duty-Cycle, different sensor options, sensing power state of the WSN (battery gauges), able to adapt to changing conditions in the RF links (power adaptation thanks to monitorization of RSSI values)
- A global computation node able to post-process data from the sensors and store data for further analysis. Large storage capability thanks to a SD card interface. External connection using Ethernet, easy and secure access thanks to ssh protocols.
- Analysis of functional specifications and requirements of the system in terms of bandwidth, data rate, frequency bands, power consumption and protocol stack to develop.
- Selection of a WSN architecture: protocol stack, frequency bands and configuration of the WSN
- Architecture of the sensor node: selection of components for the different sensors, the Tx/Rx and the software stack, energy harvesting and battery gauge circuitry. Methods for testing and measurements (serial link and power measurements)

- Architecture of the global node: selection of components, separation of global computation and WSN coordination, external interfaces with external infrastructure.
- Design of the Sensor Node schematic and layout, test plan for the sensor node, API functions for configuring the sensors and accessing the sensor data from the microcontroller. Development of software routines to measure the power consumption of the sensor node.
- Design of the Global Node schematic and layout, test plans for the global node, implement and embedded Linux in the global computation processor (ARM), communication between ARM and WSN coordinator (MSP430), global computation hardware in FPGA.
- Design of a Software Architecture for the WSN: data encapsulation and packing (data from the sensor, timestamp, RSSI, battery gauges), WSN configuration and Setup, WSN synchronization, WSN node coordination and adaptation.
- Design of Firmware for Sensor Node and for the coordinator node:
- Design of Global Computation Routines in the ARM processor:
    - WSN Setup
    - SPI communication with coordinating node
    - Communication with the FPGA and hardware acceleration
        - FFT and cross-correlation
    - Post-processing data from Sensors
        - Lowpass filtering and decimation
- Test Review in HAI facilities in Nov’13 consisted in proofing the feasibility of the work made and the preparation of the WSN toward a more extensive demo scenario at the end of the project.
- Definition of a demonstration scenario at HAI facilities. Deployment of the nodes, coordination from the global node, sensor data post-processing in the global computation hardware (ARM+FPGA) and interface via Ethernet with an external application that is able to store and visualize the data from the different sensors at different node locations and modify the WSN operation parameters.

Final results

The following achievements have been accomplished in WILDCRAFT:

- A Wireless Sensor Network (WSN) comprised of 6 sensor nodes and a global node. The sensor nodes take measures of acceleration, deformation, temperature and humidity. In addition to this, it can also monitor the state of the battery. The sensor node is ready to receive an energy harvesting source from a Thermo Electric Generator (TEG).

- Connectivity: A thoroughly analysis has been done in WILDCRAFT. Selection of communication technologies depend on several parameter: Continuous/discrete monitoring, energy consumption, amount of information needed, robustness, EMI and EMC.

- The wireless communication protocol selected has been Zigbee (2.4GHz) due to its easy deployment and fast development time within the project framework and the worldwide availability of frequency bands. The main design parameters of the WSN are the Cycle Time (time between consecutive sensor acquisitions), the Acquisition Time (the duration of one set of measurements) and the Sampling Frequency (rate at which acceleration and deformation is sampled during the Acquisition Time)

- The WSN is operating in such a way that sensor nodes can´t compete for the use of the spectrum. Sensor nodes are synchronized by the global node and have a time slot allocated to them for sending its measured data to the global node.

- A study of the battery and power requirements of the system has been carried out taking into account the current design of the sensor nodes, the wireless protocol used and different values of the above mentioned WSN parameters. The main conclusion of the study is that with current Li-Ion battery and TEG technology and using current low energy wireless technologies and low power microprocessor, it would be possible to deploy a WSN inside an aircraft with an Acquisition Time of 1s, a Cycle Time of 300s and a sampling frequency of 400Hz without having to change batteries in between major checks of the aircraft.

- The global node is composed by two main modules: *coordinator node*, which is the responsible for network management (nodes binding, addresses), and *global processor,* which is in charge of configuring the measurements, data processing and storage, decision algorithms, FPGA control and synchronization.

- From the perspective of Global processor, we based on an embedded platform with ARM processor, a FPGA and several communication ports (Ethernet, USB, Serial Port and SPI). Despite the low cost, the results in terms of performance and functional behavior were really good.

- Operating system at the global processor: we adapted a Linux version to our embedded platform. Linux offers a low-cost, rapid-prototyping capability for Integrated Modular Avionics applications. Integrated Modular Avionics (IMA) is a real-time computer network airborne systems that consist of a number of computing modules capable of supporting numerous applications of differing criticality levels. Although this is out of the scope of WILDCRAFT, if we want to reuse or integrate our functionality with other avionics systems, it is needed more research on this area.

- Data Fusion Algorithms**:** WILDCRAFT provide mechanisms to facilitate the implementation of data fusion algorithms. The use of ARM based microprocessor and FPGA ease real time processing of information. Complex operations are delegated to FPGA, while processor can attend other tasks. This is a mature technology that can ease the adoption of the solution, improve the performance and it is aligned with Integrated

Modular Avionics. More research is needed from the reliability and security perspective. We have already implemented data fusion algorithms (mainly Fast Fourier Transform, filters and Correlation), but the platform offers interface to easily plug new algorithms.

- The coordinator node offer typical functionalities of coordinator in a wireless sensor network. We demonstrated its functioning during project execution.

Potential impact and use

The following challenges and potential impacts are foreseen in the future deployment of WILDCRAFT:

- Sensor Node Miniaturization: Microcontroller and network processors are currently integrated in one-chip solutions, the same trend can be foreseen for sensors, especially accelerometers. Other sensors like strain measurements can benefit from the current integration of sigma-delta ADCs into microprocessors systems. The future will certainly see a reduction in the number of chip components in a sensor node.
- Power Consumption of the sensor node. Improvements can be made thanks to integration of RF transceiver, microprocessor and sensors and optimization of the power supply for the current actually drawn by the circuit. Power savings can be also obtained by using energy efficient wireless transmissions like new WiFi standards.
- Nevertheless, the main problem that wireless communications has to overcome is the co-existence with other wireless devices: smart-phones, tablets, laptops but also radar surveillance, terminal air traffic control and long-range weather radar. There is a good reason to believe that co-existence can be reasonably accomplish because communications in WILDCRAFT have very small data payload and therefore the duration of channel occupancy is very small.
- Battery Technology: There are certain aspects that must be studied before considering the deployment of sensor nodes with batteries around an aircraft. These aspects are considered as critical for the future of WILDCRAFT and as such are understood by the EASA in its Notice of Proposed Amendment No 2011-09 of 'Incorporation of generic SC and AMC CRIs in CS-25' which specifically targets the installation procedures of Li-Ion Batteries. In WILDCRAFT we have identified several critical design issues that battery manufacturers must consider for a safe operation of the system:
  - Specify their batteries in the environment conditions that apply for aerospace. Batteries need to be tested in temperature, humidity and charging/discharging rate conditions that are compatible with the real environment.
  - Specify battery charging/discharging behaviour with high and low temperatures.
  - To establish appropriate airworthiness standards for Li-Ion battery installations and to ensure, as required by CS-25.601, that these battery installations do not have hazardous or unreliable design characteristics.
- The power density that can realistically be obtained today with TEG is sufficient to be used for charging a battery and extend its duration. The conclusion is that even TEGs can be used as a reliable source of energy, providing enough energy to extend the battery duration beyond the period between major maintenance checks (+10000 hours)
- From the point of view of Data Fusion Algorithm, this is how we see the future development of WILDCRAFT:

- Enabling Technologies for Data Fusion are Almost ready
    - Sensors Reliability
    - Wireless Technologies
    - Power Consumption in Sensor Nodes
    - Battery Capacity & Energy Harvesting
- Data Fusion Algorithms
    - Higher abstractions in the processing of data leads to higher confidence levels in the decision making

Creating Data Fusion algorithms for SHM in aircrafts requires a multidisciplinary research effort in mechanics, electronics, information theory, digital signal processing and aeronautics. This means that a considerable support from the industry is needed but it is also true that tangible benefits have to be obtained by all the players involved: flight operator, aircraft manufacturer, maintenance industry and users. The benefits we can foresee are:

- Increased security thanks to condition-based maintenance procedures, but better security has to be perceived by the users.
- Reduction of maintenance costs (Operator): less and well focalized maintenance operations, with more information and better assessment.
- Possibility to introduce extra non-critical maintenance services based on the data gathered for the WSN

Project logo and website

WILDCRAFT

http://www.wildcraft-eu.org