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Structural Health Monitoring from Sensing to Processing

Yoann Hebrard

Abstract

Providing the best availability of aircrafts is a key driver in aeronautics industry. Monitoring system able to detect signs of failure before they happen, thanks to sensors and diagnosis/prognosis algorithms, is key for improving aircraft operability. Since a suspension system is connecting the engine to the aircraft, after hard landing, aircraft companies need to know if the suspension system is safe or could have been damaged. This chapter presents an autonomous wireless load sensing recorder development that will enable maintenance operators to make a relevant diagnosis of the suspension system by measuring the load level seen after a hard landing by connecting a portable device near the embedded sensor system. The sensor integrates energy harvesting and RFID communication modules that have been developed for this application. Data acquisition is performed by an embedded microcontroller connected to sensors. The paper is firstly dedicated to the different energy sources available in the project application (engine pods). The second part gives a presentation of the various devices developed for converting ambient energy into electric power and SHM system. The last part presents real measurement of ambient energy level from real tests in comparison to the energy needed to power the system.

Keywords: SHM, wireless sensor, RFID, energy harvesting, engine health management

1. Introduction

Based on nondestructive testing (NDT) technologies, systems known as structural health monitoring (SHM) make it possible to anticipate the deteriorations of a structure to avoid accidents. Associated with statistical processing systems, they also make it possible to optimize product life while reducing maintenance costs.

The technologies of structural health monitoring, or SHM, meet the requirement of maintaining the quality of products over time. Their main objective is to ensure the health of structures, extend their life, anticipate their failures, and enhance their performance. The SHM is therefore for the industry part of a strategy link to economical, commercial, and safety drivers.

The SHM approach is indeed both a set of processes and a control strategy [1–3]. It consists of monitoring continuously or at regular intervals the integrity of a structure by detecting cracks or alterations, such as delamination of composite materials. The proposed solutions generally include sensor networks, for example, piezoelectric or optical fiber type, coupled to signal processing systems.

The main contributions of the SHM with respect to the NDT are the integration and automation of control in a global strategy of control and/or maintenance of structures. The SHM makes it possible to improve knowledge of the structures by better monitoring, reducing maintenance interventions, and optimizing the materials used.

The ultimate goal of the SHM is the development of autonomous, continuous monitoring systems capable of detecting structure damage in real time to avoid accidents. The key challenges are in the early detection of damage, allowing optimal maintenance.

Several factors have contributed to the development of the SHM approach in recent years: numerical simulation capabilities and algorithms and the reduction of sensor consumption and its wireless communication.

This chapter presents an autonomous wireless load recorder development to enable maintenance operators to get access to loading histogram seen by an engine link in service by simply setting a portable reading device near the attachment system. Energy harvesting and RFID communication modules have been developed for this sensor considering application data such as flight duration, environmental parameters, and theoretical loading cases. Sensor system includes embedded sensors connected to a microcontroller for data acquisition and wireless communication management and energy harvesting modules. RFID technologies are used for communication and to power the device when the engine is not running. Newer SHM systems are demanding low-power sensors and wireless communication system to enable data acquisition and diagnostic automatization. Thus, several researchers have recently investigated such techniques to extract wirelessly communicate data stored in these stand-alone systems. The first part of the paper makes a comparison between different wireless communication protocols against RFID on the market considering application needs. The second part presents the RFID system developed for transmitting local data from the embedded memory of the system for analysis in a SHM diagnostic module. The last part presents an evaluation test of system communication capabilities and provides a maturity assessment on the technology.

2. RFID sensor concept and constraints for SHM application

Radio-frequency identification (RFID) uses electromagnetic fields to automatically identify and track tags attached to objects. The tags contain electronically stored information. The information can be used for different purposes. One purpose is traceability of engine parts. Today, the configuration of the engines in service must be known to respect the legal constraints. Its follow-up is therefore the responsibility of its operator. Companies realize the traceability of parts on software package in order to manage the maintenance planning, carry out the use of particular parts (life-limited parts, for example), and give a monthly status of reliability to the authority. But there is some limitation about manual software tracking. The configuration and the usage of LRU parts may not be robustly documented in the tool. In fact, the modifications carried out as part of the line maintenance can, for practical reasons, be saved later on the maintenance software. So, these data are not always up to date in the database.

The “RFID” solution seems particularly well positioned to meet this need. Its design was motivated to meet the high constraints on the configuration management at the aircraft and assembly level. It allows to know the reference of the part in a precise, fast, and automatic way. In addition, the standardization of the data in the memory of RFID chip allows a great interoperability between integrating suppliers, aircraft manufacturers, airlines, vendors, and repair shops.

But this traceability is not only related to configuration management. It can also be applied to get the real conditions of the part. RFID can be used as a sensor to gather information about real-world conditions. Alerts can be launched when some constraints have been exceeded during the usage of the parts. Visual inspection can be replaced by RFID inspection. Each of the parts keeps information about its own health..

This makes it possible to:

- Identify the MTBF specific to the use of each part (number of cycles, average temperature, number of hours in operation, etc.).
- Estimate the remaining useful life which will make it possible to value each piece individually by bringing to it a traceability of its usage.
- Follow the end of each part's life cycle by alerting the reuse of discarded parts as well as to alert in the event of counterfeit use copying a serial number already installed or unknown to manufacturers' databases.
- Minimize the risk of mounting errors, by providing tools that will check the compatibility between several parts with RFID tag.
- Give all information about a given part (manufacturing data or "birth record," inspection instructions, assembly/disassembly, troubleshooting, etc.).

RFID tag has been identified as the missing link for the realization of Integrated Engine Health Management.

But for being used in aeronautics, the RFID tag must meet different criteria and constraints. They must respect extreme environmental conditions (from -65 to $+150^{\circ}\text{C}$). They need to comply with applicable legislation and have no impact on existing systems and equipment. The usage of RFID transmission is limited to ground operations (no application on taxiways or runways or aircraft in motion). For radio-frequency, no backscatter above 35 dBuV/m and no overflow on frequency bands are allocated for other uses (including for harmonics). RFID readers must comply with GS1/EPC class 1 Gen 2 (ISO180000-63) standards operating on the 860–960 MHz compatible frequency range around the globe.

2.1 RFID sensor architecture

RFID systems use one or more RFID interrogators/readers and several passive RFID tags. For communication with the tag, the reader emits a high-frequency modulated electromagnetic wave. The tag receives the information modulated in the field, and it can answer to the request from the reader with a backscatter operation, i.e., the reflection coefficient is changed with respect to the requested information (**Figure 1**). In addition to the transmission of information between the

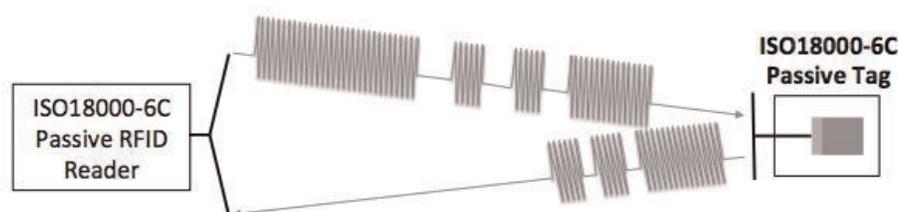


Figure 1.
RFID backscattering.

tag and the reader, the tag can receive the necessary energy for operation from the electromagnetic field of the reader.

Due to regulatory and physical constraints, the used frequency band of the passive RFID tag influences the available data rate and sets an upper limit for its operation range. HF-RFID tags operate in the near field of the reader antenna, and so the operational distances are limited between several centimeters up to 1 m. By comparison with HF-RFID systems, UHF-RFID tags transmit their data and energy by the means of the electrical far field and thus offer a higher read range from 3 up to 6 m.

The RFID sensor tag is composed of (**Figure 2**).

A sensor interface converts the change of value of a sensor into something that can be properly treated. The sensor interface is composed of a sensor readout circuitry (charge amplifier, resistive bridge, etc.) and an analogue to digital converter (ADC). The sensor interface can either be passive (the readout electronics and the analogue to digital converter are fully powered by the reader's field) or semi-passive: an additional battery powers up the interface as well as the logic.

The signal interface adapts the external signals (sensor reading, data logging, microcontrollers, display, keyboard, etc.) to the standardized RFID tag. The signal interface can be of several natures, like a serial bus interface such as SPI and I2C to connect directly the logical part of the RFID tag to an additional block such as a data logger, microcontroller, display, etc. In this case, the RFID sensor tag can be either semi-passive or active.

A logic part is the translator between the front end and the sensor interface by coding, decoding, commanding, processing, and storing information. The logic implementation usually follows a defined standard and a certain associated protocol.

An analogue RF front end typically contains a rectifier circuitry to convert RF power into DC, a clock, a modulator, and a demodulator.

An antenna is directly matched to the tag's front-end impedance to communicate with the reader. Different solutions exist for antennas, the RF front end and the logical part which are treated in the literature, whereas a low-power signal interface is a relatively new concept in the RFID context. In the case of sensor reading, the mixed signal interface should implement low-power architecture for passive, semi-passive, and even for active solutions for life span purposes. Solutions for low-power architectures are detailed in the following paragraphs.

3. Project CMOS-based RFID sensor

This PCB-based component is a passive RFID tag with embedded MCU (microcontroller unit) to manage communication protocol and application. RFID solution is a passive radio system without emission. The architecture is presented in **Figure 3**.

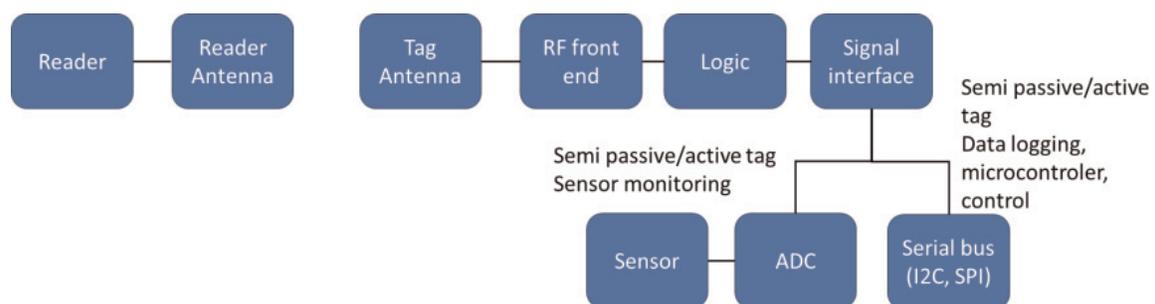


Figure 2.
RFID sensor architecture.

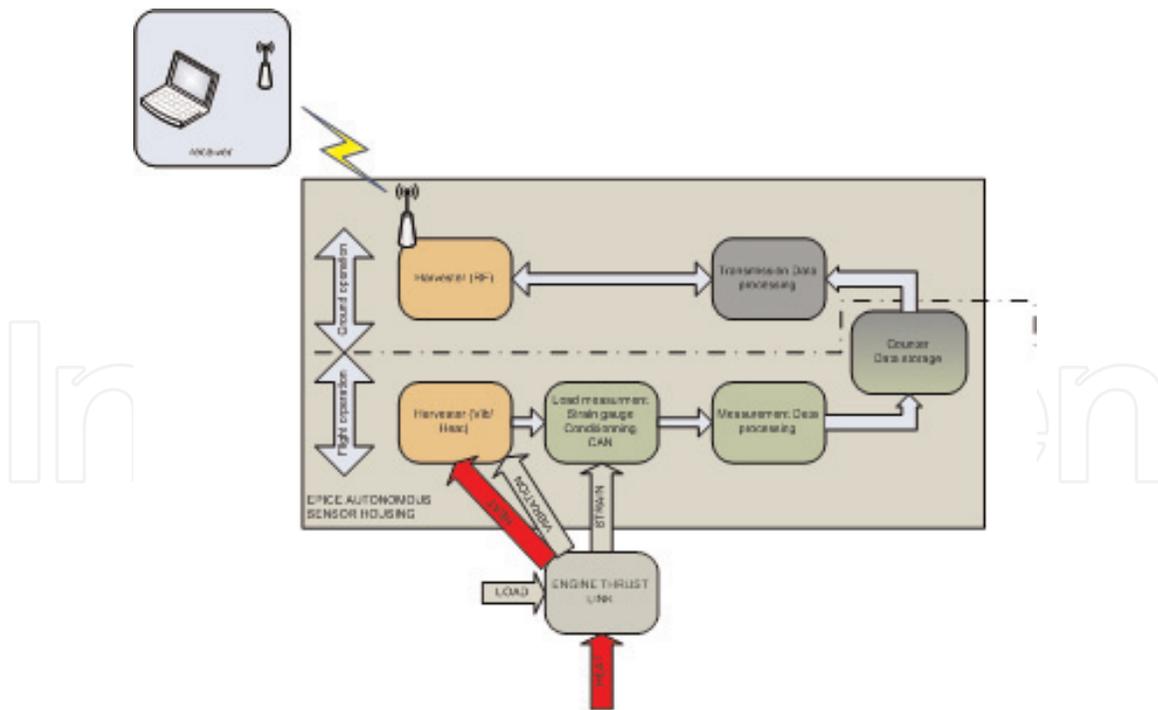


Figure 3.
 RFID sensor architecture.

From a PCB point of view, a modular approach is proposed based on a motherboard including the existing RFID tag design and harvesting boards specific to each energy source.

The device architecture includes the following subsystems:

- A strain gauge bridge. The bridge measures the load supported by the engine link. The sensor signal is stored in the NVM using the threshold crossing detection techniques. This approach reduces the amount of data to be stored since a histogram of loading class will be provided between each monitoring cycles.
- Energy harvesters to supply embedded DC converters for strain gauge bridge and the nonvolatile memory power needs. Energy is harvested from vibrations and thermal differences of the engine.
- Data and power management done by a microcontroller. Data are stored into a NVM that will be interrogated using a wireless RFID transmission. Energy harvesters provide energy, but it must be stored and managed to supply strain gauge and memory. All these parts are managed by an integrated electronic device.
- An interrogating system. It is a RFID interrogator and is not embedded into the road but approached by an operator.

Circuits for converting piezoelectric material strain into useable electrical energy have been previously described (see [4–7] for details).

The module targeted performances are the following (**Table 1**):

System power needs have been established in order to size the different harvesting modules. **Figure 4** displays voltage and current measurements done at the power input level of the system. Several commands sent at the microcontroller level allow to identify associated consumption. Cycle is quite complex; however

Subsystem	Parameters	Value
	Ambient temperature	-40/150°C max
Strain gauge acquisition	Deformation range	±2500 µdef
	Measuring bandwidth	100 Hz
	Gain/offset	Configurable
	Max sampling frequency	1000 Hz
	Resolution	12 bits
RFID UHF	Read range	15 cm/1 m in free space
	Standard	EPC GEN 2 (EU frequencies)
Vibration harvester	Frequency of ambient vibration (maximum harmonic)/ acceleration amplitude	80–110 Hz/1 g
	Variability of the vibration frequency/acceleration amplitude	Random
	Weight/volume	60 g/30 cm ³
Thermal harvester	Hot/cold temperature	80/100°C
	Heat cycle	Variable
	Weight/volume	20 g/5 cm ³

Table 1. System specification.

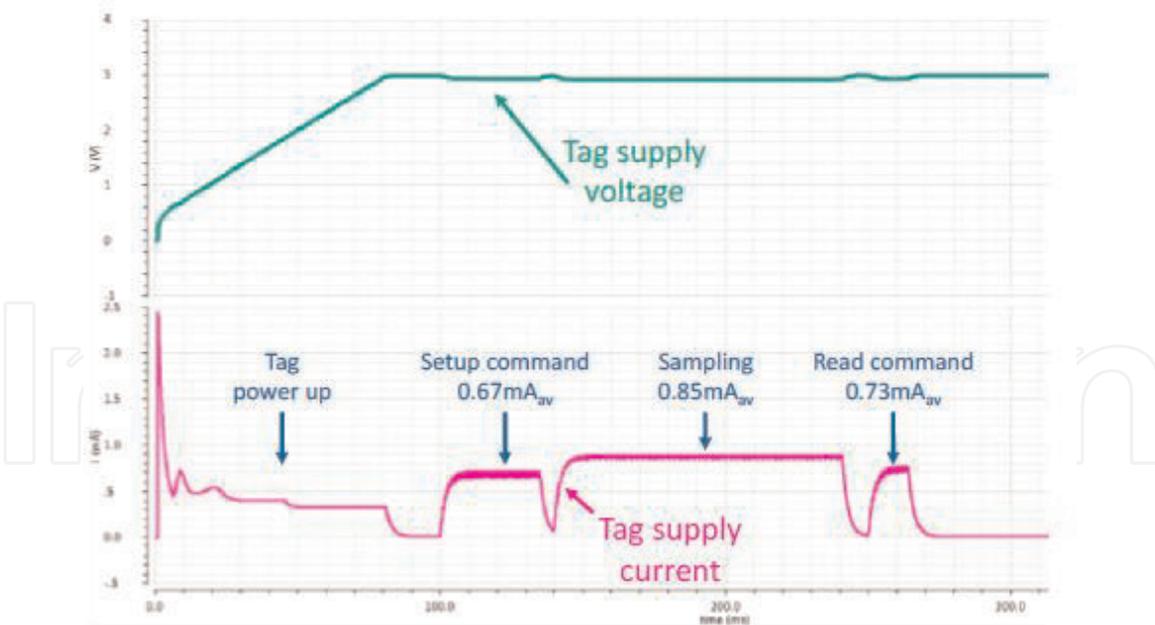


Figure 4. System consumption identification in temperature.

a power need of 3 mW has been identified for the system to work according measurement needs.

3.1 Design of key elements

Key elements for piezoelectric energy conversion include impedance matching circuits and an energy management circuit which monitor the voltage levels.

Data and power are managed thanks to the following elements:

- RFID tag: it is a small radio device also called transponder or smart tag (one can refer to ref. [8] for general details about RFID technology). The tag includes a microchip managing RF communications and a flat aerial. System tag works in the ultrahigh frequency (UHF) band (850–950 MHz) as this band offers the best compromise in power consumption with a high range ~10 m in free environment. (Details on RFID frequencies can be found in [9]).
- An electronic platform (microcontroller, volatile memory, power management circuit, strain gauge conditioning circuit): this platform locally counts the strain threshold crossings and stores them into a nonvolatile memory. Strain gauge resistance value is 5000 Ohms, to reduce the power needed to energize the bridge.

Electronic platform can be energized in two ways depending on the operational phase:

- When application is on: energy is provided by energy harvesting modules.
- When application is off: equipment does not need to be monitored, but it does when the operator downloads load counter data. Energy harvester cannot supply energy for the NVM or the electronic platform. But RFID technology gives the possibility to harvest energy from the interrogating radio-frequency wave. When engine is off, energy is provided through the RFID link.
- Reader or interrogator: it sends and receives radio-frequency data to and from the tag using antennas. A reader may have several antennas that send and receive radio waves.

3.2 Available energy sources for energy harvesting

A multitude of energy sources are available in aircraft that can be accessed with energy harvesting technologies: temperature gradient and variation, vibrations, strain, ambient light, pressure changes, electrostatic charges, etc. (**Figure 5**).

However, not all sources have sufficient potential to provide enough energy to power a sensor system. The most critical parameter for comparing these technologies in the scope of aircraft applicability is their power-to-weight ratio (per flight cycle).

Reliability of these devices is also a key criterion. Among all potential sources, thermal and vibrational energies seem most likely to meet the sector constraints [4].

3.3 Vibration harvester

The operating principle of a piezoelectric generator is relying on direct piezoelectric conversion. The internal generation of electrical charge results from an applied mechanical load. Two families of piezoelectric micro-generator can be found. The first one, named direct coupling, is directly bonded to the host structure (**Figure 6a**). The second, called indirect or seismic coupling, is connected to the host structure through a secondary element, e.g., a clamped beam (**Figure 6b**).

The project used a piezoelectric composite material (PZT type P2) manufactured as beam coupled to the mechanical trust in seismic mode. This flexible composite is made of many PZT fibers and is highly damage tolerant and fatigue resistant.

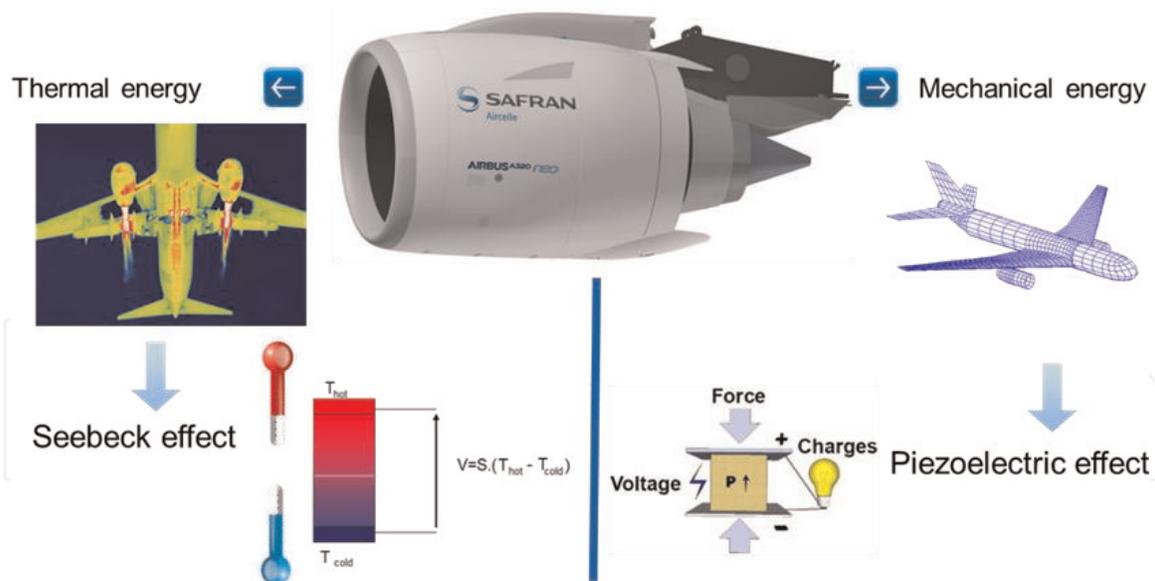


Figure 5.
Typical localizations of energy sources in engine environment.

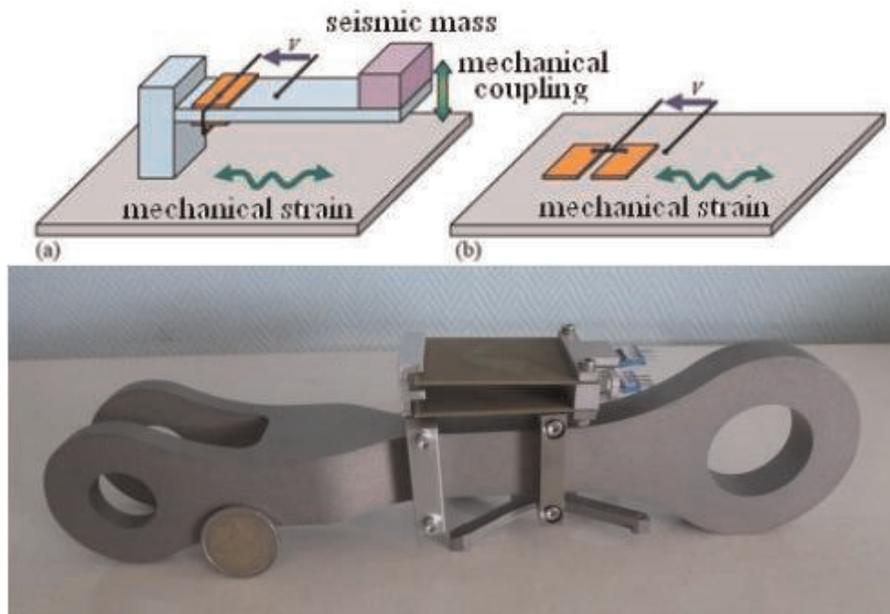


Figure 6.
Piezoelectric coupling: (a) seismic and (b) directly applied to real harvester.

The piezoelectric beams provide substantial power densities ($250 \mu\text{W}/\text{cm}^3$ at 120 Hz and 2.5 m/s^2) that make them particularly attractive for various energy harvesting applications. Seismic coupling had been chosen for the vibration harvester, because it can provide up to 10 times more energy than the classical method.

To keep a stable voltage value, synchronized switching harvesting on inductor technique is used. An electronic switch is synchronously commanded with the vibration and connects briefly the piezoelectric module to an inductance allowing voltage inversion and keeping voltage value stable.

The module performances have been evaluated by experience. A vibration harvester was mounted on a rod representative of the application. The assembly is put on a rig allowing to apply load and to heat the prototype to reach application temperature. An electromagnet is used to induce vibration in the piezoelectric beam. Vibration signal is a sinusoidal wave at 100 Hz , and several amplitudes are

applied. Power is applied to a resistive load to measure energy produced by the harvester. **Figure 7** presents the harvester power characteristic. 4 mW is produced once a vibration level of 1 g is reached.

The requested power (4 mW) by the system is generated by 1 g acceleration level.

3.4 Thermal harvester

Thermoelectricity is based on the Seebeck effect: conversion of heat into electricity. This makes it possible to save heat that would otherwise be lost. A good thermoelectric generator (TEG) must have a high Seebeck coefficient to produce the required voltage, a high electrical conductivity to reduce thermal noise, and a low thermal conductivity to reduce thermal losses (see **Figure 8**).

The engine link can be used as the hot source temperature since it is connected to the engine which is hot in service. The air around it must be cooler than the strut load and will be used as the cold source temperature.

The module performances have been evaluated experimentally. The mechanical connection of the rod is linked to heating plate, allowing a thermal gradient equivalent to the application, expecting ambient temperature (**Figure 9**).

With the circuit load, the module provides for a gradient of 10°C 500 mW of power. Two modules are integrated to the system.

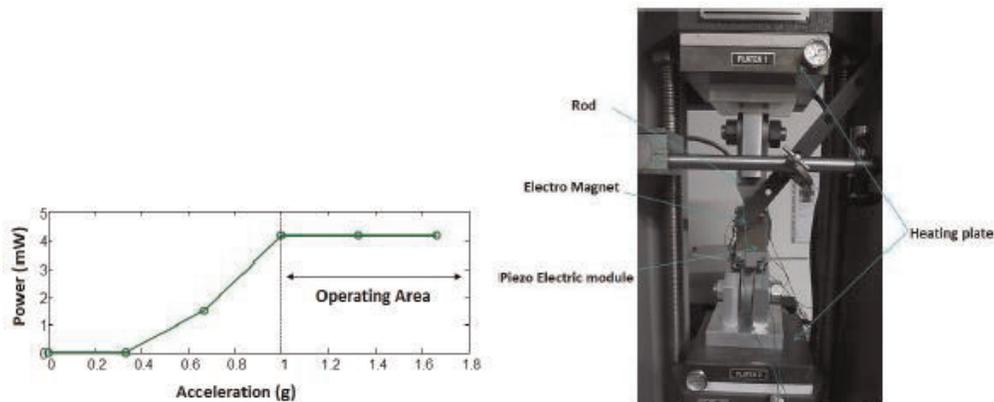


Figure 7.
Vibration harvester evaluation.

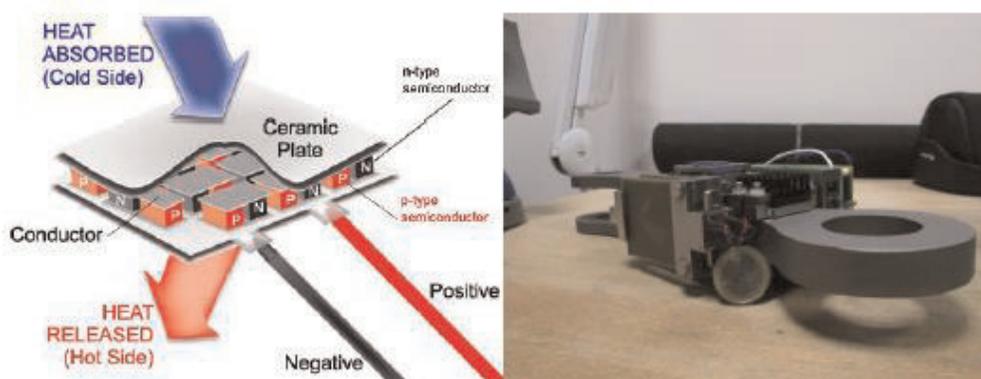


Figure 8.
Seebeck effect.

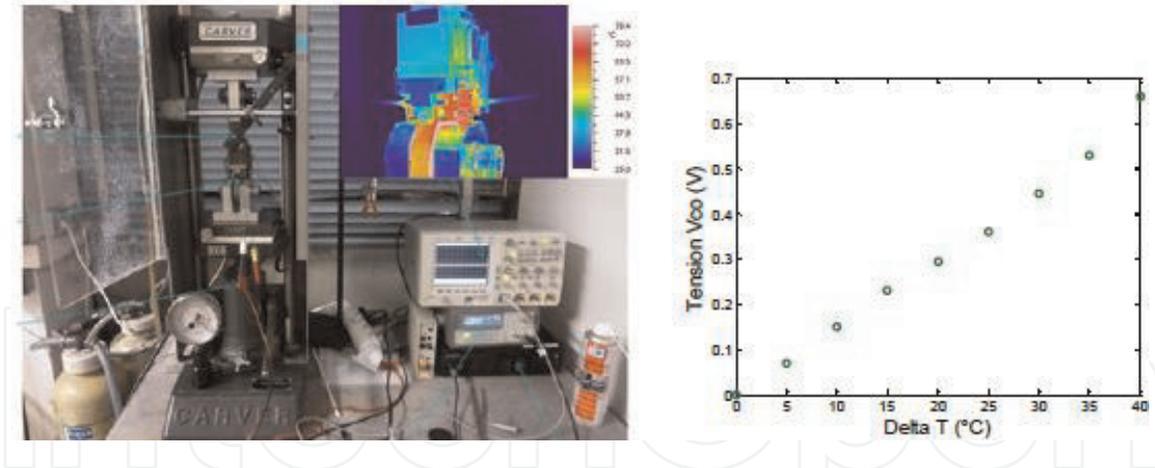


Figure 9.
Thermal harvester characterization.

3.5 Power conversion

Power management block is one of the main blocks of this module because it is supplying a whole circuit from available harvesting. It provides information to microcontroller (MCU) about the state of the tag. It indicates if vibrational, RF, or thermal energy is available. It also manages supply voltage for the whole system (**Figure 10**). Synchronized switch harvesting (SSH) techniques are used to increase vibration harvester efficiency, as detailed in Ref. [5].

3.6 RFID as a power source

The internal impedance of the chip and the antenna is given by $Z_c = R_c + jX_c$ and $Z_a = R_a + jX_a$, respectively. Thus, the power transferred to the chip P_{chip} is related to the power in the tag P_{tag} by the following equation:

$$P_{tag} = P_{chip} * \tau$$

where τ is the power transmission coefficient:

$$\tau = 1 - |\Gamma_{tag}|^2$$

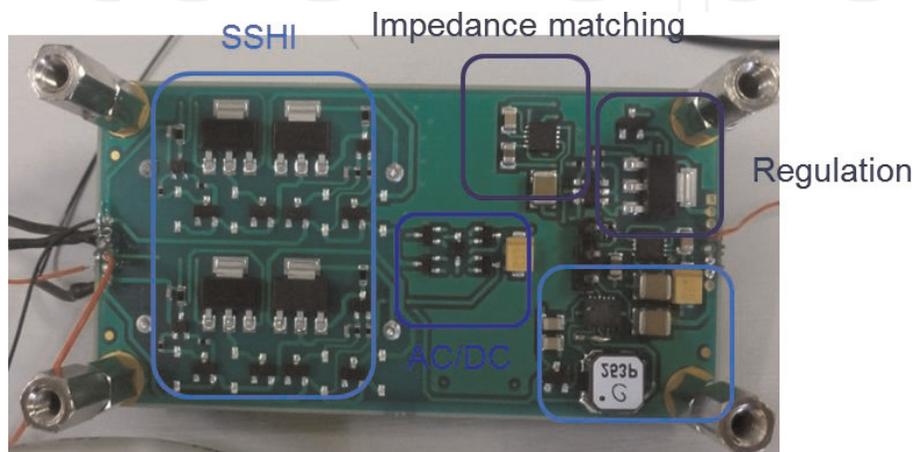


Figure 10.
Power conversion board.

And Γ_{tag} is the reflection coefficient from the antenna and the chip:

$$\Gamma_{tag} = \frac{(z_c - z_a^*)}{z_c + z_a}$$

So τ can be represented by the following equation:

$$\tau = \frac{4 * R_a * R_c}{|Z_c + Z_a|}$$

Increasing the value of τ will increase the power reaching the tag, increasing, consecutively, the distance from where the tag can be active by the amount of power coming from the reader.

Finally, τ is a coefficient that varies between 0 and 1. To increase the reading distance, the power transmission coefficient should be as much as possible equal to 1. That means that the impedances of the antenna and the chip should be matched:

$$z_c = z_a^* \Rightarrow \tau = 1$$

The theoretical distance from where the tag can be read is calculated using Eq. 1, where λ is the wavelength, P_{trans} is the power sent by the reader, G_{reader} and G_{tag} are, respectively, the gain from the reader and the tag antenna, and P_{th} is the tag chip sensibility, which is the minimal power that the IC must receive to be activated. The value of $P_{trans} * G_{reader}$ is fixed as the maximum power that is possible to be sent by the local legislation in the desired frequency band.

$$Read\ distance\ r = \left(\frac{\lambda}{4}\pi\right) * \sqrt{\frac{P_{trans} * G_{reader} * G_{tag} * \tau}{P_{th}}} \quad (1)$$

Commercial readers are normally very sensitive. The minimum power requested to decode without ambiguity the tag signal (the downlink) is considerably smaller than the one characterizing the uplink. Therefore, for passive UHF-RFID tags, the maximum distance from where the system can work is only governed by the uplink for most of RFID systems.

Far-field UHF-RFID antennas are usually designed in three steps: firstly a loop is designed around the IC to work as an inductor and compensate the capacitive part of the chip. The system composed by the loop and the chip will resonate around the desired UHF frequency. Secondly, the radiation element that is usually a folded dipole is attached to the antenna. Finally, the impedance matching and radiation gain for the tag are tuned and optimized to increase its reading distance. This step is very important in the way it permits a better understanding of the antenna electrical behavior. It is in that step that the designer can find a correspondence between the geometric dimensions and the EM properties of the antenna [6].

For some classical HF antennas, there are analytical formulas that can be used to calculate the expected EM properties of the coil in order to simplify the design part. However, for UHF-RFID antennas, these formulas are very uncommon, and most of the process of the antenna design is empirical. In [7] a method to automatically design UHF-RFID antennas by using a combination of a genetic algorithm and the 3D EM simulation software CST is given.

Besides the classical dipole antenna, there are several researchers that are trying to create new designs to surpass specific problems that most of the time accrued in practical applications. Nested slot, inverted-F configurations, and patch antennas are some of the most well-known designs [8].

Even if the UHF-RFID is being used in a large number of economic areas, there is already a large market where this technology did not bring any answer. Metal placed with RFID tags is one of the greatest challenges to the RFID technology, and a lot of researches have been putting large efforts to solve this problem in the last decade. In particular, the classical dipole antennas are not effective when put near to metallic surfaces.

This specific problem is explained in **Figure 11**, which shows that the image dipole below the metal surface has an opposite current from that of the original dipole. If the space between the dipole and its image is very small (much less than one wavelength), then the total effective current approaches zero. Therefore, the total radiation field is negligible. The RFID is then unable to capture power from the reader.

Looking for a solution to this problem, some ideas have been explored in the last years and are well explained in [6, 7]:

- Inserting high permeability isolator
- Increasing the distance between the antenna and the metal surface
- Using frequency-selective surfaces
- Using an anti-metal antenna design

Dipole antenna demonstrated weak communication capability for the project application environment. An anti-metal antenna design has been investigated [10–22] to propose an alternative to dipole antenna as shown (**Figure 12**).

4. Testing in a laboratory environment

Once evaluated in a laboratory environment, the demonstrator was integrated to engine tests. Packaging of the system was made of silicon sealant. A full-scale demonstrator was evaluated and submitted to qualification testing before ground engine testing. **Figure 13** presents the system validation phase:

- The demonstrator is assembled on a real thrust link.
- The thrust link is mounted on a hydraulic press able to generate compressive force similar to the real application.
- The press plates can be heated allowing to apply application temperature level to the system.

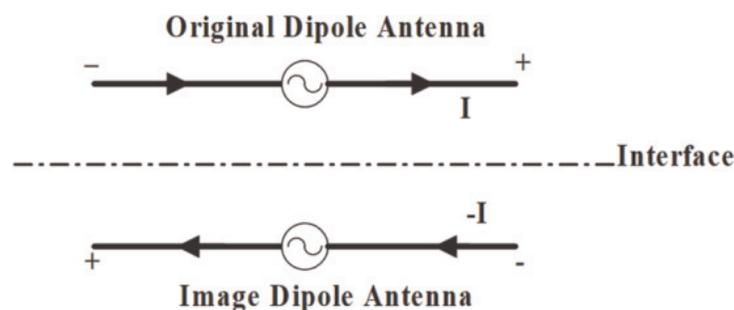


Figure 11. A dipole antenna above a perfect electric conductor (PEC) and its image [6].



Figure 12.
Reading distance with dipole antenna.

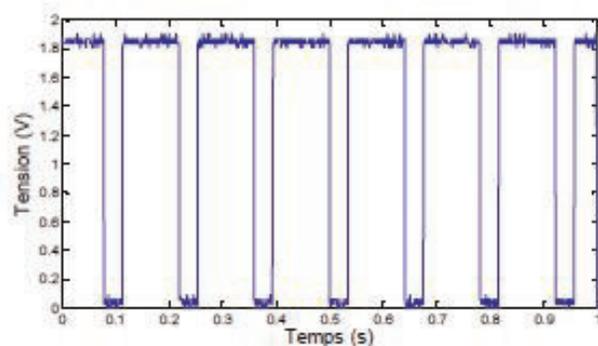


Figure 13.
Laboratory validation of the sensor system.

- A vibrator is used to induce vibration to the piezoelectric beams of the vibration harvesters. Levels applied are random spectrum, according to application specification.

Compressive loads were applied to the mechanical link with the system clamped to it. Thermal difference (80/120°C) was applied at each end of the link to establish a thermal gradient close to the application to feed thermal harvesters. A piezoelectric buzzer was used to apply excitation to the vibration harvesters. The regulated voltage from the power module was checked and also the read write memory voltage output at the microcontroller level.

The autonomy of the system was reached for a thermal gradient of 10°C for the thermal harvester and a vibration level of 1 g at 100 Hz (**Figure 14**).

The system was submitted to ground testing inside a real engine. During the tests, system failed to be autonomous. Measurement done externally showed that the vibration and energy sources were lower than forecasted for the sizing of the system.

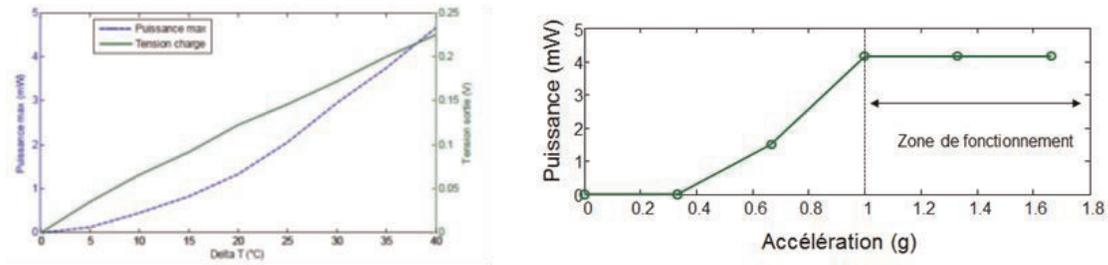


Figure 14. Thermal and vibration harvesters' characteristics.

5. Conclusion

Optimization of energy harvesters is a system-level problem that involves several design requirements on the power processing stages. Deploying an energy harvester on its own will yield poor power densities, which is why additional circuitry is needed to implement features such as synchronized switch harvesting or impedance match between harvester and load electronics, energy storage capabilities, and output voltage regulation.

Each energy harvester is differentiated by its transduction mechanism, and therefore the equivalent source impedance model must be derived for different harvesters and available energy densities variation from the environment. By matching the source impedance to that of the load or by applying appropriate switching, the maximum power transfer is achieved from the harvester to the load under optimal conditions **Figure 15**.

The project provided key data to identify the gaps to be solved for developing energy harvesting module in engine environment.

Despite several energy sources available in airplanes and helicopters, engineers and scientists have to face numerous challenges when trying to achieve reliable devices able to capture sufficient energy to perform any useful work.

Energy sources available must be characterized in terms of level, availability, and frequency range. This is a prerequisite before sizing the harvester module to ensure capability to produce enough energy.

Energy management is also key: the best practice approach is to use a comparator on the energy storage module to prevent the system from drawing energy from the storage element, unless enough energy was stored to perform the programmed sensing/processing/logging communication tasks. This allowed the energy storage elements to store up enough energy to perform for the specific task, before allowing

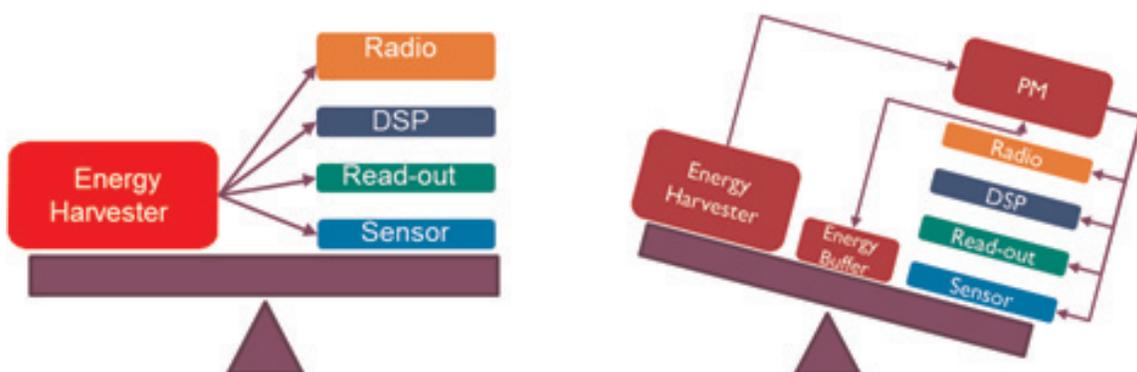


Figure 15. Constraints in designing an autonomous system.

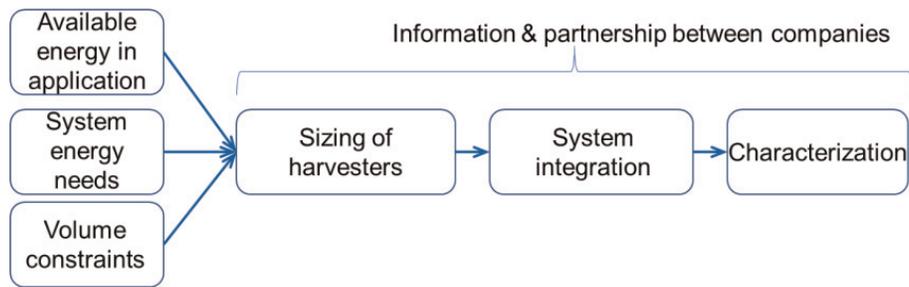


Figure 16.
Ideal workflow for developing an autonomous system.

the task to be performed. This is the key approach to adapt the sensing tasks in applications where the ambient energy levels are low, variable, or intermittent.

Energy harvesting based on vibrational and thermal effects has been chosen for the module development, thanks to their better reliability and performances than others. In the case of vibrational energy, the production of micro-generators using either electromagnetic or piezoelectric conversion elements seems the most promising. Both conversion principles are complementary although the electromagnetic one is more effective in the low frequency range (100 Hz).

For thermal energy harvesting, the system operation is based on the principle of the Seebeck effect. Such technologies are investigated because of their robustness and resistance to environmental stresses, i.e., mechanical and thermal. Nonetheless, a number of challenges must be solved before achieving efficient wireless autonomous sensors for real aeronautical applications, such as long-lasting self-sufficient operation of sensors, selection of wireless protocols, etc.

According to **Figure 16**, the goal of maximizing the amount of the harvested energy involves several factors, including electronics optimization, characterization of the available ambient energy, selection and configuration of energy harvesting materials, and integration with storage mechanisms, along with the power optimization and power awareness design. This project tried to address these issues in an integrated manner from the multidisciplinary engineering perspective. The performance of thermal and vibration harvester prototypes had been validated and tested in real environment.

Future perspectives are optimization of the transduction mechanism of the harvester, power awareness, and storage element to validate an upgrade of the prototype in experimental environment derived from the real measurements.

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