Cross-functional design of wireless sensor networks applied to Aircraft Health Monitoring

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COVER SHEET

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ABSTRACT

The purpose of this paper is to describe the relationships existing between the various levels or functions encompassed when designing a Wireless Sensor Network in the specific area of Aircraft Health Monitoring. More precisely, cross-dependence between topics such as implementation technologies, environmental energy capture and storage, sensor design, and communication issues are covered. Various practical examples in the field are briefly given to illustrate different correlations.

INTRODUCTION

Aircraft Health Monitoring (AHM) is one of the major challenges faced by aircraft manufacturers [1] [2]. This activity is aimed at proposing an innovative and comprehensive Global Aircraft Maintenance service for aircraft customers.

Main areas of application of AHM are the airframe, the main engines and the main systems (such as Auxiliary Power Unit - APU), all major contributors to Aircraft "Delay and Cancellation". One of the major issues is the prediction of failures to prevent structure or system damages by anticipating the maintenance action necessary to avoid "events". Such predictive service is especially relevant for the Structure Health Monitoring (SHM). SHM therefore consists mainly in the monitoring of corrosion, of cracks and of impact damages taking place during the

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aircraft life. Particular attention is paid to SHM due to the fact that integration at Aircraft level is not fully demonstrated yet, although SHM technology bricks have become available for a few years (or are in development already for more innovative solutions). In addition, there is a potential direct added value for companies, which are both aircraft integrator and airframe manufacturers.

Despite the fact that only limited implementations of AHM have already been done using wired technology [3], because of the gain associated to a wireless architecture, support of AHM by Wireless Sensors Networks (WSN) based on MEMS technology, is envisioned by major aircraft manufacturers. It is generally considered as a powerful tool to:

- decrease inspection costs,
- optimize margins in mechanical design, and consequently, reduce aircraft weight, fuel consumption and emissions of greenhouse gases.

MEMS technologies are attractive for AHM since they are easy to install, less intrusive at usage, less costly at production, and intrinsically lightweight. However, AHM may not be considered as a supplemental maintenance service only because the aircraft structure is already sized to undergo stress and fatigue for the entire aircraft lifetime, as well as to answer to the regulatory rules. A main objective of AHM is the extension of the scheduled maintenance tasks to take into account actual aircraft operation constraints. The extended scheduled maintenance task could become a business benefit as well as a further step in terms of certification approach.

The purpose of this paper is to describe the general process and challenges of designing a WSN applied to AHM. While a global description will be given, a set of examples will also be presented to illustrate various cross-optimization issues.

CROSS-FUNCTIONAL DESIGN

General Architecture

In the above context, a network of a relatively large number of self-powered MEMS-based nodes would perform sensing, data processing and wireless transmission of information. In such a WSN, the most obvious wireless energy supply system consists of batteries. However, whatever the batteries performance and size, they only store a limited amount of energy and exhibit a limited lifetime therefore placing an unacceptable upper limit on the network lifetime itself (given the fact that nodes may be placed in remote areas with very limited access). More important, at temperature levels encountered at high altitude in unpressurized areas far from engines (typically –60 Celsius) their yield is drastically reduced while unacceptable safety issues (thermal runaway and fire) are raised.

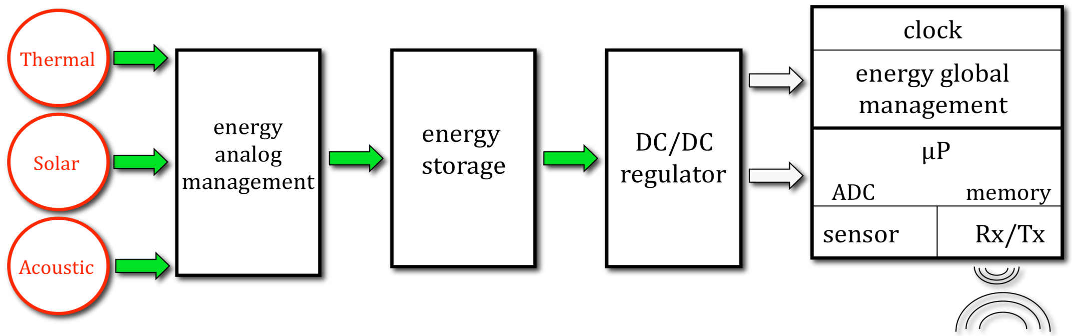

Figure 1. General architecture of the node of a wireless sensor network.

This is why, as depicted in Figure 1, energy capture from the environment may be required. This energy will be stored before being used to power the functions of the node: sensing, signal processing and data transmission. These various functions are discussed in the following.

Energy Capture

One drawback to moving toward a wireless network installation is the poor reliability and limited useful life of batteries needed to supply the energy to the sensor, radio, processor, and other electronic elements of the system. Regarding AHM, in addition to the required lifetime (~ 20 years), batteries are prohibited since the wireless sensor node could be placed in locations without temperature regulation that could result in safety issues. Indeed, lithium-ion batteries can rupture, ignite, or explode when exposed to high and very low temperature environments, for example in an area that is prone to prolonged direct sunlight. In addition, accidental short-circuiting a Li-ion battery can also cause it to ignite or explode. This limitation has to some extent curtailed the proliferation of wireless networks. Fortunately, the batteries can be eliminated through the use of environmental energy capture techniques [1], which use an energy conversion transducer tied to an integrated rechargeable power storage device, then enabling the wireless sensor node an almost infinite lifetime.

For energy capture, two principles may be considered, called energy harvesting (continuous source) and energy scavenging (intermittent source). However, availability of energy is in both cases limited, and for such a self-powered network, energy is therefore a critical issue, and hardware design must consider energy as a main constraint. In other words, the design process of the functions to be implemented in the node must first take into account the available energy given the fact that physical constraints in terms of size or weight ultimately limit energetic resources.

Considering the potential energy sources within the studied context, a tentative list is as follows: solar energy, variations of atmospheric pressure during flight, thermal gradients, aircraft structure mechanical vibrations, acoustic noise, currents from aircraft static electricity dischargers, electromagnetic energy emitted by wires and electrical appliances.

It is worth mentioning that multiple energy sources may be considered since it may occur that a single category would not be enough to power a node during all phases of a flight. More precisely, time shifts in the availability of environmental energy together with intrinsic different time constants of the transducers and the by-nature synergy between scavenging and harvesting may praise for such a multi-source configuration. Figure 1 presents the functional diagram of a node illustrating such a strategy.

Back to the energy sources likely to be considered, a lot of them (such as solar, thermal, acoustic…) are transmitted through power fluxes Φ (W/m^2). Considering the number of sensor nodes d per unit area, the mean power p (W) required for operating a node, the area a (m^2) required per sensor node to capture this energy, it comes:

$$p = \Phi . a \tag{1}$$

The total area A (m^2) per square meter devoted for energy capture is given by:

$$A = d.a \tag{2}$$

with necessarily

$$A < 1 \text{ m}^2 \tag{3}$$

If $a \ll 1$ m^2, the sensor network density and therefore the meshing resolution of the medium to be instrumented can be freely determined by the application requirements. If not, the meshing density is energy driven, the parameter d being governed by energy considerations only. In other words, the energy likely to be harvested puts an upper limit to the resolution of the sensor network meshing. In Figure 2 the two situations are graphically depicted. As an illustration, we may consider a practical application (for instance for air pressure distribution monitoring) where the outside (i.e. illuminated) surface of an aircraft component is covered by solar cells: the sensor node consumption then determines the solar cell area needed to power it and consequently the sensor and meshing maximum density.

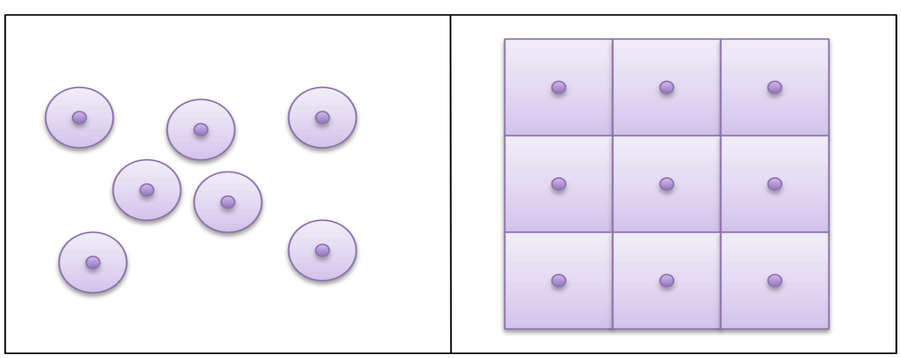

Figure 2. Left: application driven topology – Right: energy driven topology. The grey areas represent areas a of equations (1,2), the small dots correspond to the measurement locations.

Finally, considering the implementation technology for the energy capture function, it is worth to mention that it is not given for sure that MEMS constitute the generic solution as a small size implies a low captured energy flux: in the above example, the solar cells are likely to expand themselves outside the node package where sensor, energy storage and signal processing units are located, to cover the area required to harvest the needed solar energy.

Energy Storage

Although in terms of energy loss, immediate use of the captured environmental energy by the WSN node would be more efficient, an energy-storage device is required as an energy buffer between the WSN node and the energy source. Additionally, long-term energy storage may be desired to budget for future energy consumption when scavenging or harvesting efficiency would be low.

In our application context, the use of a (rechargeable) battery being unlikely, electrical double-layer capacitors, also named super-capacitors or ultra-capacitors, are the solution for transient storage. They store energy electrostatically between solid electrode and oppositely charged electrolyte ions. They offer a high capacitance in a small volume. However, conversely to batteries, they do not provide a fairly constant output voltage, the output of a supercapacitor dropping from full value to zero during discharge: a voltage regulator is therefore required for biasing the signal processing part of the WSN node (see Figure 1).

However, the capacitance value of these key devices must be optimized vs.:

- duration of scavenging phases (by imposing the storage of almost all scavenged energy),
- electrical output resistance of transducers (considering their impact on time constant of the charging of supercapacitors),
- self-discharge,
- output amplitude of transducers.

It must be stressed that, at this stage, the parameter of importance is the transfer through the transducer of a maximum of energy from the environment to the supercapacitor, whatever the conversion yield, all energy not captured being ultimately lost. Conversely, later energy treatment must favour yield.

To illustrate this issue, we have considered the case of AHM being performed in non-illuminated areas of a commercial jet. The energy is here captured from thermal gradients, and we have plotted in Figure 3 the amount of energy stored in various supercapacitors connected to the output of a thermogenerator. This thermogenerator uses the transient thermal gradients appearing between the outside air and a small water tank during the phases of a flight when the altitude of an aircraft varies [4]. It is worth mentioning that energy, and not power, is the parameter of interest given the fact that this application deals with energy scavenging and not harvesting. In this situation, optimisation of the storage device is obviously crucial.

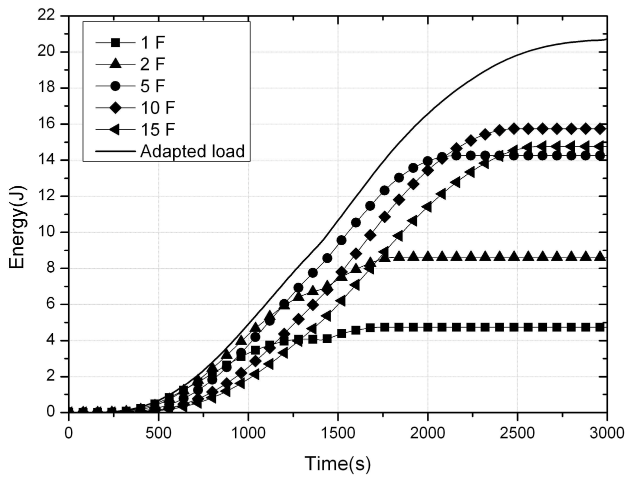

Figure 3. Energy scavenged and stored in various supercapacitors vs. time. The case of an adapted resistive load is given for comparison. The energy transducer is a thermogenerator submitted to a transient thermal gradient when altitude varies from ground level to 10 000 m between take off and cruise phases, with a ground temperature of 15°C.

It appears that if optimisation must been done first vs. electrical parameters, such as thermogenerator output impedance, interestingly also application conditions (i.e. in the example of Figure 3, duration of the climb phase of the flight) are crucial. More precisely, if the time constant of the storage circuit is longer than the scavenging phase, or conversely if the supercapacitor value is too low, the maximum energy transfer is not achieved between environment and storage. Said differently, the optimum capacitor value cannot be computed here without taking into account typical flight scenarios.

Sensing and Signal Processing

The sensing and signal processing functions are the core and essential purposes of the WSN nodes. They have to fulfil the objectives of the high level application for which the network has been devised. However, their requirements in terms of direct power consumption and data storage and transmission, must be kept to a minimum compatible with the available energy and transmission capacity of the wireless link. There again, the design of the sensing function cannot be done independently from other functions.

As an illustration, let us consider the issue of AHM that could be performed on the blades of turboprops, such as those of the future A400M Military airlifter. Each of the four engines powers an 8-bladed propeller. Rotation speed is of the order of 800 rpm; blades are manufactured from composite fibres. AHM objective could be to monitor blade balance, vibrations (either permanent or transiently induced by an impact) and over-speeds.

The first issue is that of sensing: the choice of a unique sensor is therefore mandatory to avoid multiple acquisition chains. Consequently, the choice of a 3D accelerometer makes sense given the fact that it may obviously monitor vibrations but also rotating speed through the oscillating centrifugal acceleration (see Figure 4).

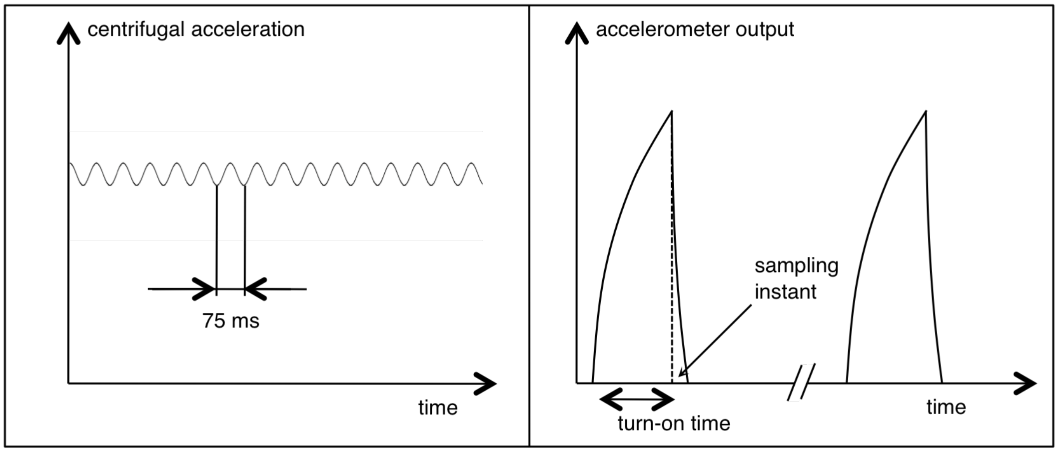

Figure 4. Left: centrifugal acceleration showing the blade rotating period signature at 800 rpm. Right: sensor sleep/active sequences showing that the accelerometer is operated in the transient mode only to speed up measurement.

However, even with a *single-sensor* design, if sensor were activated permanently, it would very likely exceed the maximum available power. This is why the sensor needs to be in a sleep state most of the time, being turned on periodically. This period implicitly defines the sampling frequency.

Given the fact that the blade rotating speed corresponds to a frequency around 15 Hz (see Figure 4) and that the blade free oscillation frequency is of the order of a few tens of hertz, a sampling frequency value around 50 Hz appears appropriate to monitor over-speed and abnormal oscillations. Consequently, the parameter of choice for the accelerometer is the turn-on time: a sensor exhibiting a small turn-on transient allowing minimum average power consumption. For a typical accelerometer, exhibiting a continuous supply power and a rise time of respectively 1 mW and 1 ms, for a ratio between active and inactive phases of 1 ms/20 ms, the mean power used by the sensor falls to 50 µW (the sleep mode consumption is less than 1% of that of the active mode).

The second issue regarding sensing is the amount of data to be processed, stored and ultimately transmitted. Considering the above example, the ADC output could be 14 bits at 50 Hz. This flow of data would locally be processed to detect abnormal events in terms of vibrations or speed. These events are supposed to occur rarely and therefore most of the data is flushed. Conversely, if a warning threshold is exceeded, the event is recorded and stored in a memory. The memory will be read through a wireless link. However, the purpose of AHM being only to trigger - when needed - a specific inspection of the blade, it is not required to permanently transmit a large flow of data carrying unnecessary information. More limited information such as date of event, type of event (over-speed or vibration), category of event (from *minor* to *impacting safety*) would be sufficient. A binary word between 5 and 10 bits should be enough, these bits being the payload of the frame to be transmitted. However, an overhead would have to be added, such as the sensor physical identification. Nevertheless, the small number of frames together with their small size would make the Medium Access Control (MAC) procedure less costly in terms of latency and energy.

From the above example, it is obvious that an appropriate choice of both the sensor hardware and sensing procedure may keep to a minimum both the power removed from the energy capture unit, and the data flow (and indirectly the power consumption) of the wireless communication unit.

Communications

Wireless communications are qualitatively recognized as being an important contributor to energy consumption, while impulse UWB minimizes it [5]. A lot of efforts are therefore done to develop multi-hop transmissions, directive antennas, emission power control, and when the communication channel is not permanently active to devise efficient MAC schemes to avoid frame collisions and unnecessary long listening phases. Alternatively, a dramatic change in the nature of the WSN architecture would be to use the radar signature of passive sensors [6], provided that this signature would be affected by SHM parameters. A radar (30 GHz and above) located in a powered area of the aircraft, would scan the area where the sensors would be deployed. These sensors would require no other energy than that provided by the radar beam. The flow of information would be analogically conveyed by the reflected beam and would not suffer from information collisions. Information would be treated and aggregated by powerful circuits located by the radar. The benefit is there obtained from the mix-up of the following functions: energy transmission, sensing, and communication of information.

CONCLUSION

We have illustrated through different examples the unexpected relationships taking place between various design levels of a WSN applied to AHM such as technology, energy capture, sensor spatial density, sensor choice and operating conditions, local data processing and transmission. These design cross-constraints are very application specific and a one-size-fits-all solution is very unlikely. However, the knowledge of these cross-design constraints is the key for a successful implementation.

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