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Autonomous power supply for aeronautical health monitoring sensors

M Bafleur¹, V Boitier¹, D Bramban¹,
J-M Dilhac¹, X Dollat¹, J Féau² and S Jugé²

¹LAAS-CNRS, Université de Toulouse, CNRS, INSA, UPS, Toulouse, France,

² Airbus, ³ Altran Technologies

Abstract. New applications of embedded systems are envisioned in the context of aeronautics. However, the increasing burden of on-board cabling requires wireless solutions. Moreover, concerns such as safety or system lifetime often preclude the use of electrochemical energy storage. Ambient energy capture, storage and management are therefore key topics. In this paper we illustrate these concepts by describing an actual implementation in the engine harsh environment of an Airbus A380. A thermogenerator was used to harvest ambient energy and the electronics associated with it allows the local system being energy autonomous. All items were devised and tested in order to meet the criteria of DO-160G aeronautical standard. The set of equipment was mounted on aircraft, and submitted to tens of test flights during roughly a year, in very various flight conditions.

1. Introduction

Numerous new applications of embedded systems, and more specifically of sensor networks are today envisioned in the context of aeronautics. Generally speaking, sensor networks will play an increasingly important role: among others, monitoring the aging of the structure of the aircraft (Structural Health Monitoring - SHM) making it possible to only carry out repairs when necessary, thus saving time, weight (by decreasing mechanical margins) and therefore fuel.

However, the deployment of new wired sensor networks comes up against the complexity of electric networks already present in commercial aircrafts: as an illustration the total cable length is around 500 km for an Airbus A380. This praises in favour of wireless networks, but wireless means that each node of the network has to be energy autonomous. The simplest solution is therefore to rely on an energy reserve provided by an electrochemical battery featuring a high energy density and a weak self-discharge. However usage restrictions such as the required regular replacement of the battery, and risks (fire or explosion) associated with their operation in harsh environments, cannot be ignored. Consequently it is worth to investigate ambient energy harvesting combined with electrostatic energy storage using supercapacitors, in order to provide the required energy autonomy.

2. Requirements

The goal of this project was to arrange SHM sensors (temperature and crack detectors) deployed in the engine area (figure 1), and a local acquisition system (datalogger) transmitting data to a concentrator [1]. A module to harvest ambient energy and the electronics associated with it are, on the other hand, aimed to make the local system energy autonomous. The presence of permanent thermal gradients, found as soon as the engine is started, made sense to choose thermogeneration as the source of electric energy. Power has to be supplied to the datalogger under 5 V. The power consumption of the specific datalogger to be built for this project by another partner [2] was initially estimated around 2.5 mW, with 300 mW power spikes during data transmission. The system is not active when engines are stopped and energy storage has to be scaled only for such power surges. In addition, all system has to adhere to DO-160G aeronautical standard setting minimum performance requirements in terms of

environmental conditions such as temperature, pressure, acceleration, vibrations, fire, electromagnetic interferences (EMI), etc. The corresponding certification process is not presented in this paper, except for some specific points.

3. System architecture

3.1. Thermogenerator

The global structure of energy management system is depicted in figure 2: a limited storage based on two supercapacitors is used to deal with power surges without oversizing the thermogenerator (TEG).

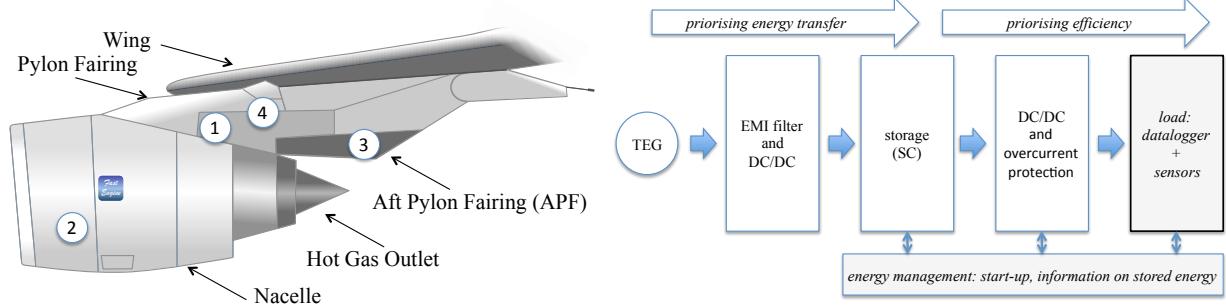


Figure 1. Engine's immediate environment: (1) thermogenerator (2, 3) sensors (4) energy and signal processing electronics.

Figure 2. Architecture of energy management system (TEG stands for thermogenerator, and SC for supercapacitors).

As shown in figure 1, the system is cabled locally over large distances. The reason is as follows: basically the sensors are placed in close proximity to mechanical parts (nacelle and aft pylon fairing) that they monitor. These parts are by nature submitted to aggressive environments (temperature-wise here), incompatible with electronic devices. The thermogenerator itself obeys another constraint: it is placed along the path of a thermal flux not necessarily present neither at the sensor nor electronic system locations. These local cabling raises the issue of using a wired connection to an already existing power cable installed nearby. However, in this paper, we will consider the above installation as a proof of concept of energy harvesting usage in the very specific context of aviation.

We first designed and manufactured a module incorporating the thermogenerator (figures 3 and 4) to be placed in a cell of the pylon. This cell was identified as likely to provide a sufficient in-flight thermal gradient between cell wall and ambient air. The thermogenerator is in contact with the pylon wall through the intermediary of a stainless steel bearing plate. The thermogenerator is sandwiched between this plate and a copper exchanger, and is placed under pressure by the intermediary of two titanium flanges. The electric output of the thermogenerator is linked to a high temperature electric connector certified for aeronautics. This connector is set in the plate by an intermediary part made from a high temperature polymer support to lower the temperature of the connector. This polymer is also the material used for the inserts in flange-holders to lower thermal bridges.

The assembly was mechanically designed in such a way that in case of fire (the standard assumes that in this case the wall of the pylon is brought to 1100°C), as soon as the thermogenerator's semi-conducting elements (Bi_2Te_3 , melting point 573 °C) and materials made of polymers will have melted or burned, the module remains attached to the wall of the pylon, and that especially all of its metallic pieces remain interdependent. Digital simulations have shown that the copper exchanger will not melt under conditions imposed by the DO-160G standard. For the selected position for the thermogeneration module, the thermal gradient between the wall of the pylon and the air inside was initially evaluated at cruise level between 120 and 180°C, according to weather conditions and the flight altitude. The wall temperature could itself exceed 250°C on the hottest days (Maximum Hot Day). The selected thermogenerator (*KELK Komatsu KTGM161-18*) was tested in a climatic chamber. In a worst-case scenario, i.e. for a 110°C gradient, the device provided 39 mW at maximum power point, power sufficient enough for our design brief.

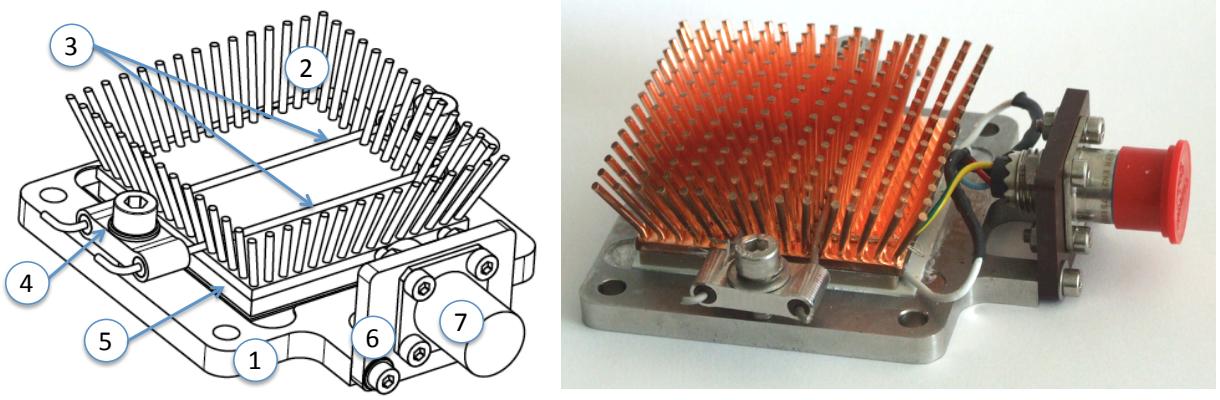


Figure 3. Perspective view of the thermogeneration module. (1) plate (2) exchanger (only one part of its shafts is shown) (3) flanges (4) flange-holders (5) thermogenerator (6) connector-holder (7) electric connector.

Figure 4. Detailed view of the thermogeneration module. The total weight is 497 g. Overall dimensions are 9 x 12 x 3 cm.

3.2. Electronic energy management system

Already shown functionally in its concept in figure 2, the more detailed layout of the electronic energy management system is shown in figure 5. We very briefly describe it below.

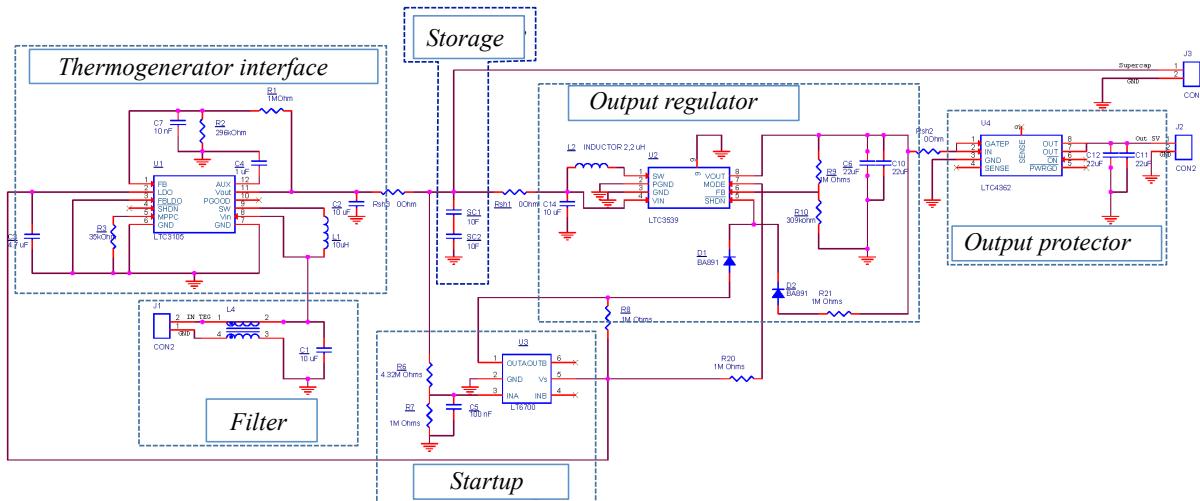


Figure 5. Overall structure of the electronic energy management system.

A common mode filter aimed at protecting the system against conducting electromagnetic interferences was placed at the electronic card input. Then there is a continuous boost regulator operating at a maximum power point (using a user predefined setpoint). It also protects the supercapacitors from over voltage and provides a regulated auxiliary voltage for the startup management circuit. Storage is fulfilled by two BCAP0003 ultra-capacitors by Maxwell, connected in series (equivalent to 1.65 F). Regulating the output voltage is fulfilled by a boost regulator (step-up), whose output voltage in our case is set at 5 V. Finally, and although the regulator already has integrated safeguards against over currents, we added, in an interface with the load, a specific protection circuit.

Figure 6 gives the electronic card built. To fulfill the DO 160G standard, it was coated (Electrolube DCA SCC3) in order to protect against fluids, and to prevent electric arcs (dielectric rigidity of the coating: 90 kV/mm). The card was integrated into a 316L stainless steel housing to comply with the fireproofing standard. Aeronautical high-temperature connectors (Souriau, series 2997 and 3649) are finally used in the connection between the thermogenerator and the load.

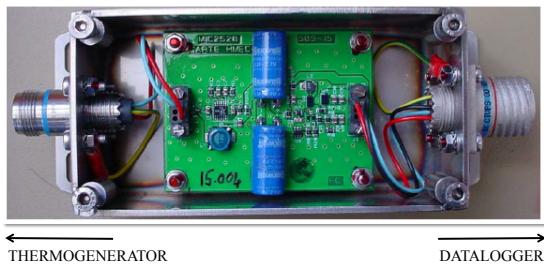


Figure 6. Electronic energy management system in its housing. The total weight is 504 g.

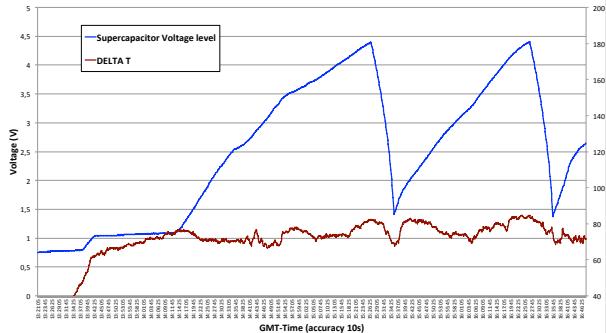


Figure 7. Thermal gradient (bottom) and charges and discharges (top) of supercapacitors during flight, induced by energy storage and periodical powering of the load.

4. Flight testing

The above energy management system has been correctly operating in flight for 1 year. The datalogger was cabled to be either powered by aircraft power network (to guarantee continuous operation) or by the harvester as soon as the supercapacitor voltage was high enough. Unfortunately, the datalogger mean consumption initially supposed to be around 2.5 mW was in practice 10 times higher and the harvester could not power permanently the datalogger as shown in figure 7 (supercapacitor voltage decreases when the harvester supplies the datalogger as the harvested power cannot compensate the consumption). In effect the datalogger was powered by the harvester 15% of the time for flights at low or medium altitude. At high cruising levels (typically 10 000m) air pressure was too low to permit sufficient thermal exchanges by convection.

5. Conclusion

The designed above system (thermogenerator and associated electronics) is robust and has been operating properly for over a year although temperatures and vibrations are significant. Unfortunately, due to imprecise initial specifications and optimistic environmental data, it could not power the load permanently in all flight phases. Nevertheless the above work is a good proof of concept. Future work should include a mechanical design to operate with forced convection (using relative wind) to foster thermal exchanges at high flight levels.

Acknowledgments

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