Autonomous for perpetuity smart sensors - Review of actual implementations and technologies focused on energizing solution based on micro-supercapacitors, highly reliable in any environmental conditions

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0. Abstract

The need for more detailed and variety of information necessary to build informational and energy efficient, ubiquitous and reliable systems known nowadays an explosive evolution from 2 billion in 2011 to 18 billion in 2022[1.]. Many challenges must be satisfy and this should overpass important obstacles. Only several could be mentioned: energy consumption in the context of permanent extension of replacement of necessary sources of energy; long range in communication and easy, automatically setup of connection between new generations of sensors; necessity to include the semantic features into the complex aggregation of information exchanged into the modern networks; extremely cost effective; secured and reliable system networks. The actual context in this field request a complex and very deeply analysis of every component of system but the basis still remain the energising solutions. In this sense the extremely expected very long time of exploitation (for perpetuity suitable), the extremely low consumption, the capacity to provide adequate, opportune and already pre-processed data, the capacity to auto-aggregate using machine to machine communication (M2M) or Internet of Things (IoT) concepts as simplified and ready to used protocols and procedure are only several of the challenges at which this new sensors must respond [2.].
The micro-hybrid electric storage of energy devices (MSC) or systems represents a prolific way to boost the technology of smart sensors for perpetuity. As consequence, this technology will permit better adaptation of solution at more demanding needs of energy for next generation of sensors and will allow the development of more reliable, available and secure solutions. Using the combination of batteries and MSC, a large range of load demands and power can be better satisfied assuring a good energetic security margin in functioning of system. In the same time, the reliability, availability and span time of the system will increase significantly.
The hybrid storage solution for perpetuity sensors are in the same time less sensitive related to the temperature variation domain.
The paper proposes a simple functional design indications related the dimensioning of storage system, especially the hybrid one function of applications needs. This should realize an optimal compromise between the energy and power requested and don't includes data about price and other potential parameters that can suffer optimization.

1. Introduction

The need for more detailed and variety of information necessary to build informational and energy efficient, ubiquitous and reliable systems known nowadays an explosive evolution from 2 billion in 2011 to 18 billion in 2022 [1.]. Many challenges must be satisfy and this should overpass important obstacles. Only several could be mentioned: energy consumption in the context of permanent extension of replacement of necessary sources of energy; long range in communication and easy, automatically setup of connection between new generations of sensors; necessity to include the semantic features into the complex aggregation of information exchanged into the modern networks; extremely cost effective; secured and reliable system networks. The actual context in this field request a complex and very deeply analysis of every component of system but the basis still remain the energising solutions. In this sense the extremely expected very long time of exploitation (for perpetuity suitable), the extremely low consumption, the capacity to provide adequate, opportune and already pre-processed data, the capacity to auto-aggregate using machine to machine communication (M2M) or Internet of Things (IoT) concepts [2.] as simplified and ready to used protocols and procedure are only several of the challenges at which this new sensors must respond. A crucial and primordial aspect is related to the efficient implementation of the local energizing system. This is formed by two main components: the harvesting system able to collect infinitesimal quantity of energy from sensor's environment, and capability to store efficiently this amount of energy for signal acquisition, processing and tele-transmission of data. Additional aspects such as: temperature operation domain, inherent loses of energy during it storage, processability and autonomous function, reliable settlement and functionality in context of network integration are also critical and important aspects that should be addressed.

2 Actual stage of system's components development

A generic structure of smart sensors systems designed for perpetuity is shown in Figure 1. The review of potential signals envisaged by such system is done in [3.] and [4.].

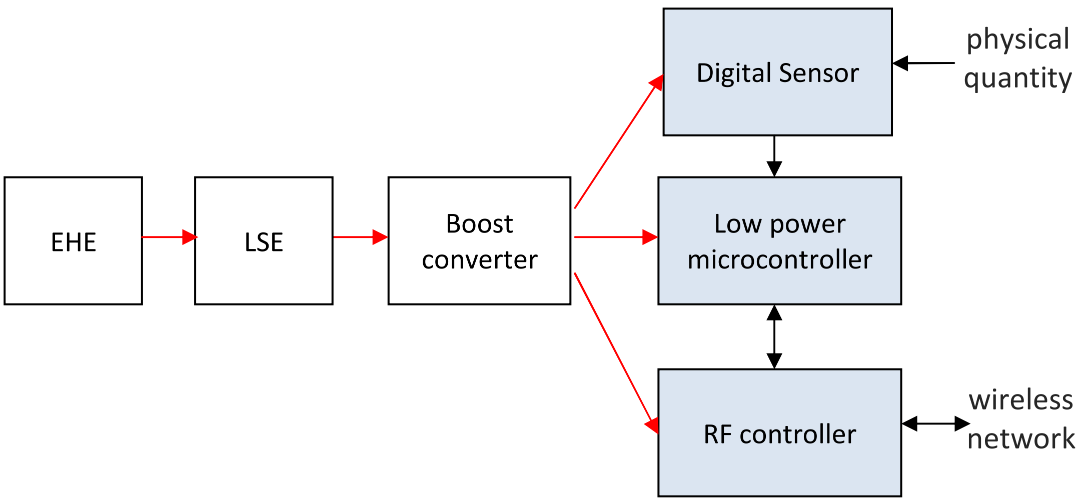

Figure 1 Structure of a sensor for perpetuity. EHE = Energy Harvesting Element (Light, vibration, temperature, etc [15.]). LSE = Local (hybrid) Storage Element

The variety of signals acquired is very high: chemical parameter sensors (partial oxygen, CO, CO_2, NO_2, etc), particles sensor, smog, moisture, water sensors, mechanical sensors, acceleration gyroscopic, inclinometer, displacement, speed sensors, electric sensors current, electric and magnetic field sensors, temperature, pressure, air flow sensors, biochemical

ion-selective sensors and more other sensors. All of these need a source of energy in order to assure their functionality. This could be the result of artificial energizing system, for example by using local power supplies like batteries of supercapacitors or must be connected to an external power supply by wires or wireless by electromagnetic field. In first case, the batteries and more that the supercapacitors needs to be connected with another elements that is the receiver (converter) of energy harvested from environment that could be: a piezoelectric generator -capturing mechanical vibrations; a light base sensor like a photo-voltaic system; a thermal element able to convert the difference of temperature in voltage; an electro-magnetic based on induction, power supply or other similar elements base of ion separation membranes [15.].
A review of potential usable energy resources is done in [5.] table 1. Several relevant data we mentioned: for acoustic signals the minimum level of energy usable is 0.003 $\mu W/cm^3$ at 75dB, respectively 0.96 $\mu W/cm^3$ at 100dB; for temperature variation this is 10 $\mu W/cm^3$ and Pescowitz in 2012 have demonstrated that can produce 40mW on a device having 0.5 cm^2 at 5°C difference of temperature; for sun light this is 100 mW/cm^2 in free air, and for mechanical vibration this is 200 $\mu W/cm^3$. In [27.] a comparison of different vibration-to-electrical transducers is done. In case of micro-mechanical system capacitors at 2,52KHz were reported a generator of 8.6µW obtained in 75mm^3 with 114.6μWcm^3 power density [28.]. In [29.] is reported an implementation of a piezoelectric generator that at 2.25m/s^2 85Hz, generate 1.7mW, volume of generator 5.1 cm^3, respectively 335$\mu W.cm^3$ power density.
Looking at the whole harvesting channel an important role is play by the step up inverter. The energy efficiency in case of multilevel inverters depend the modulation strategies control based on fundamental and high switching frequency [20.]. A value of energy efficiency conversion could be considered more than 85% using for example LTC3459 IC circuits [21.]. As related application implementation in [4.] is illustrated a systems for acquiring the ExG (ECG, EEG, and EMG) signals from patients that consume only 19µW.
The signal processing unit should satisfy several conditions and respond at the constraints related energy consumption, processing and communication capacity, protocols for communication, stability, availability and reliability on a large domain of functioning temperatures, etc. Other conditions that must be satisfied are related to the shape, the dimensions, the environmental constraints and integration into the working behaviour, materials and their compatibility and also their eventually system's recycling possibilities. These features should be also taken into account at the design of such systems.
The diversity of solutions from multichip solution to system on chip (SoC), from simple general ISA to specific ISA dedicated to reduction of power consumed on the market are a huge variety of solutions.
Another aspect that should form a parameter that determines a series of compromises is related to the firmware that endowed many SoC solutions. The principle that stay at the base of chip and system design are illustrated in [22.], where for example the design and implementation of the ultra-low-power digitally controlled oscillator (DCO) arrive at a very low power consumption, respectively 140µW/200MHz the technology used being CMOS at 90nm. In [23.] the aspects related SoC are detailed described. First is analysed the influence of increasing of density on functional elements on the chip, from 90nm, to 45nm, 32nm and even 22nm. A detailed analysis is made on Dynamic and Static Power Consumption, Design for Manufacturing (DFM) and the design of multi-voltage level fault tolerant chips. The well

known formula of chip power consumption P, that illustrate the quadratic dependency from supply voltage V, and linear dependency from frequency f is evoked too.

$$P = k * V^2 * f \qquad (0)$$

where k is a chip technology dependent coefficient that is concretize in principle Dynamic Voltage Frequency Scaling (DVFS). A detailed analysis about this subject is done too.

A very important aspect is related to the complexity of the chip and functionalities implemented on it. For example, the inclusion of wireless transceiver will increase significantly the power consumption especially during receiving and processing of data. Here the role of transceiver adaptive amplifier play an important role: from one side, this assures the increasing of distance with reliable transfer of data, but in the same time increase significantly the power consumption. That signify that the designer should very attentively treat the design problem especially related the most close from reality functioning condition for the system. In [24.] an example is reported, respectively in case of WSN application the power consumption is very low. Using the WiseNET transceiver with the WiseMAC protocol [24.], a relay sensor node consumes about 25 microwatts when forwarding 56-byte packets at every 100 seconds. A conclusion of paper [23.] is that a multi-disciplinary approach is mandatory in order to obtain very good performance from the point of view performance/consumption ratio. In this process the role played by MSC could be essential, especially when the systems should function in harsh condition of temperature and for perpetuity functioning demands.

In [25.] two important formulas illustrate the power consumption on different stages of these.

$$W_a = \sum k * f * V^2 = N_G * f_{CLK} * W_G \qquad (1)$$

where W_a is the active power consumed, f is clock frequency, V is voltage of circuit power supply, N_G are the number of circuit gates f_{CLK} the commutation frequency of gates, and W_G the specific commutation power/gate.[25.], and the second one regards leakage power on the chip and is:

$$W_p = N_T * I_{off}(V_t) * V = N_G * W_G \qquad (2)$$

where N_T are the chip' transistors number, I_{off} is leakage current/transistor, V_t is the voltage on transistor and the time period in off stage of transistor [25.]

Related the processing units connected to the sensors and used to convert, implement advanced computation functions and communication protocols implementation their actual trend is to integrate into a SoC all these facilities.

Thus, X1000 Intel family of processor [6.], [7.], AM18xx, Am17xx [8.], Exynos 7420, Snapdragon 810 chips [10.] and other represent only several families of processors that have as firmware implemented the advance power management and also the IoT protocols allowing a very complex interoperability and working using native features directly on the cloud. The maximum frequency and the consumption are the principal features that are optimized on those chips. A special attention is paid for the influence of the communication protocol that assures the data transfer but also status information and commands from supervisor system to the smart IoT sensor. The IoT compliance bring an important feature

the semantic property of data exchanged that is essential feature used in fusion and informational integration of data at network level, especially on Internet.
The consumption of X1000 chips integrated in Edison SDK is 13mW in standby without any radio transceiver activated, with Bluetooth 4.0 is 21.5mW and in Wi-Fi the power consumed reach 35mW [6.]. In case of AM18xx family the processor are designed with a complex strategy for saving energy Dynamic Voltage Frequency Scaling (DVFS) and the power consumption can vary from 1.2mW till 720mW in case of OMAP family[9.].

3. Solution for energizing the hybrid source systems

The solution for storage of energy are fundamental in order to reach the maximum reliability availability and life span (desirable during the life span of the system) as power supply of sensors, processing system and also communication system.
The most frequent solution for energize of the perpetuity sensors use the batteries, especially Li-Ion batteries that presents a very good energy density, and acceptable temperature domain. Unfortunately, for perpetuity sensors such solutions don't satisfy from the point of life span and need even after ten years to be exchanged. Another aspect that is important is related to the specific of load demands of wireless sensors, where the load profile presents important peaks. This peaks, accelerate the normal aging process of batteries and accelerate their degradation. A holistic and detailed analysis of batteries behaviour used for wireless endowed with embedded systems is done in [26.]. Several processing are important in case of such systems that assure in fact some self services. For example, the system should realize a deep management of energy in which the most important steps is represented by determination of Depth of Discharge (DoD) and State of Health (SoH) of batteries. The monitoring of these parameters is resource consuming (computing resources and also energy resources). A detailed evaluation of energy consumed is dependent of structure, organization and type of hardware implementation and suppose a permanent functioning of the services and present a high complexity in system design. Even if the successive stages reach by system in functioning are well known the inter-correlation between load and temperature of environment where is placed the sensor generate large variations of predictions about remained quantity of energy or need a more complex algorithm for management of the system. In [26.] using complex algorithms and a detailed and complex model for batteries and system as whole, is reach a accuracy of life span prediction of 95%. A problem that hasn’t a response is related to the completeness of models, simulation and validation related especially to the variation of communication assumptions.
An more reliable and optimistic view can be considered as result of progress realized in the field of nano-materials used for micro-supercondensator technologies (MSC). These devices don't need a complex analysis of their status and the life span and temperature domain are larger in comparison with the batteries. The main disadvantage of MSC is related to the restrained energetic density capacity.
A holistic vision about this kind of solution is included in [11.] table 7 page 139. Thus, function of template of the stationary phase in [11.] and [12.] and the type of electrolyte the specific capacitance can vary significantly. in case of liquid phase exfoliation (LPE) of graphene LPE reach 351 Fg^{-1}, 110$kWkg^{-1}$, and 12.5$Whkg^{-1}$. [13.] , and in case of MnO_2 nano-rods electrodeposited onto CNPs the capacitance reach 389Fg^{-1} [14.]. The data should be see into the context also of thermal, chemical or ultrasonic treatment applied on stationary

phase and of course function of electrolyte. Some data are relevant in order to define the limits of the energy, respectively the energy that could be stored, respectively the maximum power that could be provided. Even if the authors are focused on graphene[1] application we should recognize that for the micro-supercapacitors (MSC) based on Electric Double Layer Condensers, this implementation reach a significant performance made this ideal to work integrated with the energy harvesting elements.

In case then the energy demands of smart for perpetuity sensor don't satisfy the application requirements, a compromise that will significantly increase the performance of the systems. This compromise can be implemented using different hybrid storage solutions:

i. by combining of two or many small batteries and a supercapacitors as independent entities in conjunction with a simple electronic control system able to maximize the depth of power cycling processes to be done on MSC and to protect in this way the high load peak demands from battery.
ii. by using devices, or storage cells them self presenting the capabilities for balancing in a different ration the fast release and medium time release charge. As is indicated in classification present in [11.] the storage solutions used for perpetuity sensors could be:
    a. hybrid-supercapacitors (simultaneously EDLC and pseudocapacitor) and
    b. pseudocapacitors

both presenting different ration between the Faradic and non-Faradic storage that can satisfy the complex energy/power demands of applications.

Also, even this way was not significantly investigated till now, for smart for perpetuity sensors we consider on interest the simplification of functioning for the system by relaxing the variation of power supply voltage domain fitting it close for maximum acceptable values of processor and transceiver. In this way, a more simple energy efficient system can be build-up.

In both situations, with or without a good power supply voltage stabilization the generic energetic balance can be write in this case (equation 3) as follow:

$$W = \int_{t_1}^{t_3} p_1(t)dt - \int_{t_2}^{t_3} p_2(t)dt \qquad (3)$$

where W represents the energetic balance of the for perpetuity system and should be strictly bigger as zero. A supra-unitary coefficient should be adopted and this should be $k \epsilon (1.2 ; 3)$ function of degree of reliability desired for the system. In equation 3, t represents the cycling period representing the desired time necessary between two successive measurements cycles done by the perpetuity smart sensor: $t \epsilon (t_1,t_3)$ is first period of time corresponding to the charging process of MSC, p_1 represent the instantaneously power value produced by harvesting element in period $t \epsilon (t_1,t_3)$, and p_2 correspond to the consumption of processing and communication elements in the period $t \epsilon (t_2,t_3)$. This period corresponding to the signal acquired, processed and transmitted of the data to supervisor system. Of course, this equation will be affected by energy efficiency of intermediate and conditioning element such as: step up converters, switching devices and losses appeared

[1] graphene represent a hexagonal allotropic form of carbon, with absolutely remarkable properties: reach at room temperature μ=2.510^5 cm^2 V^{-1}s [16.]$^-$, Young modulus 1TPa, intrinsic strength 130GPa [17.], thermal conductivity k until 5300Wm^{-1}K^{-1} [18.] and more than 10^6 bigger electro conductivity compared with copper [19.]

into the storage elements and also on the own inherent consumption of system's components. Thus, the above equation 3 becomes equation 4:

$$W = \int_{t_1}^{t_3} p_1(t)dt - \int_{t_2}^{t_3} p_2(t)dt - \sum_1^n p_i \, \Delta t_i \qquad (4)$$

where *n* are the systems components that present losses, p_i are the mean power value of losses corresponding at element *i* and Δt_i represent the period during the losses are active in case of *i* element. The same condition as in case of equation 3 should be respected.

In case when try to speculate the maximum voltage variation for the SoC and sensor and we will use only MSC elements as storage, the dimensioning of this storage device should respect simultaneously the following constraints:

i. the system should store a minimum total energy that is:

ii.

$$W_{max} = \frac{1}{2} \cdot C \cdot V_2^2 \qquad (5),$$

where W_{max} is the maximum energy necessary to assure the functioning of for perpetuity system in reliable condition;

iii. in the same time:

$$W_{max} = k \cdot W = \int_{t_1}^{t_3} p_1(t)dt - \int_{t_2}^{t_3} p_2(t)dt - \sum_1^n p_i \, \Delta t_i \qquad (6)$$

k is supra unitary coefficient established function of type of application.

iv. and also:

$$\Delta W = \frac{1}{2} \cdot C^* \cdot (V_2^2 - V_1^2) \qquad (7)$$

Thus, we will choose the maximum value between C and C*, as result from equations (5) and (7), respectively:

$$C = \frac{2 \cdot W_{max}}{V_2^2} \qquad (8)$$

and

$$C^* = \frac{2 \cdot \Delta W}{(V_2^2 - V_1^2)} \qquad (9)$$

In case of hybrid storage system solutions, the residual amount of energy W_{min}, respectively:

$$W_{min} = W_1 = \frac{1}{2} \cdot C \cdot V_1^2 = W_{Bat}[Ah] \qquad (10)$$

In this case, practically the battery will offer the basis energy and the DoD of battery could remain near of 0%.

A practical example, using only battery is offered by Yuen in [27.] and this shown the following data for a smart for perpetuity sensor of temperature: regular start-up 600µs, energy/power consumed 49µJ/81.7mW; micro-power start-up 545µs, energy/power consumed 15µJ/27.6mW, temperature conversion1.41s, energy/power consumed 36.1µJ/25.5µW, wireless transmission4.17ms, energy/power consumed 113µJ/27mW, respectively the sleep time period energy/power 22.4µJ/1s. The mean value over a period of measurement session was: 884µJ, respectively 27.6µW average power.

4. Conclusions

The micro-hybrid electric storage of energy devices or systems represents a prolific way to boost the technology of smart sensors for perpetuity. As consequence, this technology will permit better adaptation of solution at more demanding needs of energy for next generation of sensors and will allow the development of more reliable, available and secure solutions.

Using the combination of batteries and MSC, a large range of load demands and power can be better satisfied assuring a good energetic security margin in functioning of system.

In the same time, the reliability, availability and span time of the system will be significantly increased.

The hybrid storage solution for perpetuity sensors are in the same time less sensitive related to the temperature variation domain.

The paper proposes a simple functional design indications related the dimensioning of storage system, especially the hybrid one function of applications needs. This should realize an optimal compromise between the energy and power requested and don't includes data about price and other potential parameters that can suffer optimization.

About the price the authors consider that now is not the moment to take definitive considerations because the fabrication series and the daily improvements of materials and technologies used for fabrication of such devices can't give a appropriate image about price evolution.

Some "simple" applications, such as the smart for perpetuity sensors for thermal comfort on interior of cars can significantly improve the control system and also the energy efficiency.

The future works will be oriented to include the aging characteristics in case of design flow and to find out better solutions related the micro-inverters or even to eliminate this by new topological solution for energy harvesting elements in correlation with the storage system and the information processing and communication unit.

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