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► **To cite this version:**

Vincent Le Cam, Marianne Lossec, Regis Le Maulf, Laurent Lemarchand, William Martin, et al.. Towards autonomous wireless sensors systems in Civil Engineering. Paving the way to an “energy oriented design method”. International Workshop on Structural Health Monitoring, Stanford University, Departement of Mechanics, Sep 2011, Stanford, France. <hal-04479654>

HAL Id: hal-04479654

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Submitted on 27 Feb 2024

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Title: Towards autonomous wireless sensors systems in Civil Engineering. Paving the way to an “energy oriented design method”

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ABSTRACT

Last years, SHM and similar non-destructive techniques communities have developed and published solutions and efforts regarding wireless and smart sensors solutions. Those numerous works clearly demonstrate the immediate gain that wireless solutions imply especially when applied to civil engineering structures: cost-effectiveness, simplicity, more mobile and reusable devices, etc.

As an evidence, the main input constraint when designing a wireless instrumentation (sensor or other) refers to energy saving. In that prolific domain, numerous solutions are designed with more or less positive results. Most known or commercialized solutions refers to improved and optimized electronic design that save energy. But, in most of the case, the consequence resides in sensors that offer lower sampling rate (up to some Hz), lower computing abilities, and limited wireless communications: distances, rates, durations.... Moreover some other functionalities are forgotten when sensor is too focused on energy: synchronization, intelligence.

The aim of this paper is to pave the ground of methods and approaches that refers to energy harvesting to make wireless sensors able of high level functionalities. More than some general considerations, this paper also includes real and technical feedback that French Public Works Laboratory (IFSTTAR) obtained through the application of its generic and wireless sensor platform (*PEGASE*) in collaboration with SATIE Laboratory (from ENS-Cachan).

This article first makes the distinction between the sensor's sub-entities from the energy point of view: sources, charge, storage. Then, in view of optimal dimensioning (solar cells, battery capacity), concept of *degree of freedom* is introduced as well as a concept of *quality index* from energy point of view. The article proposes a method that details how to deal with those parameters to improve the Wireless Sensor Networks design step.

INTRODUCTION

The list of parameters that could model what is -or what should be- a wireless sensor is complex to establish: cost, integration, capacity, number of channels, autonomy on battery, wireless abilities, data processing level, etc.

From author point of view a first assumption is proposed: for high level sampling rates and/or complex algorithms and/or long term instrumentation, additional energy source(s) must be added to wireless sensor [1].

For the moment, the most efficient and disseminated external source consists in using solar cells coupled to battery controlled by an hardware and software manager.

A second assumption is that, for a specific wireless sensor need, engineers and developers make originally optimal choices from energy point of view during designing phase: sober components, optimal placement, processor activity reduced to the minimal need, hardware and software including energy manager such as MPPT algorithms, etc. When wireless sensor design is validated, battery and solar cells technology choice and dimensioning can be determined with parametric specifications according to sensor location (e.g. latitude, luminosity, solar cell technology).

Because reducing solar cell and battery dimensions are two obvious objectives, from the above basic and typical assumptions, new concepts can be considered to improve the WSN design.

PEGASE PLATFORM

In order to illustrate ideas brought by this article, the use case of PEGASE and its results are given. PEGASE is an high level wireless and generic platform specified and designed by IFSTTAR [2].

Its major high performances are the following: use of a DSP as core processor, runs a μ CLinux as embedded OS, use of a GPS module to ensure localization and UTC time-base up to some μ S, implement Tcp/Ip/802.11.b wireless communications.

Its generic attributes are: an open-source C library that cover all peripherals drivers, a plug and play concept where a simple and inexpensive daughter board is designed for specific use-case (e.g. to read a temperature sensor, an accelerometer,...).



Figure 1. PEGASE generic and wireless platform: marketed kit, acoustic implementation.

Since 2009, PEGASE is marketed and sold through A3IP french company [3] in hundreds of samples. From customers, PEGASE can be seen as solution device as well as a development and fast-prototyping board.

All along the present article, PEGASE platform is intended for a specific acoustic use-case where the system monitor acoustic waves for structural health monitoring needs; for instance: wire-breaks in cable detection.

CONCEPT OF DEGREES OF FREEDOM

Definition and identification

One major idea driving the present article resides in the *degrees of freedom* (DOF) identification. This first step of the method invites engineers to reconsider the WSN system as the sum of power-consuming functionalities that has not to operate continuously or whose importance varies in time or whose performance is tunable.

Each behaviour of the wireless sensor has to be identified from the energy point of view, each of them can be considered as a degree of freedom.

Every wireless sensor has its own specificities (hardware choices, software assignment, etc.) but those analyses can be illustrated through the work applied on PEGASE platform:

TABLE I. PEGASE PLATFORM IDENTIFIED DEGREES OF FREEDOM

DOF	Description
Wireless TxPower	In most of cases, RF chip that implement wireless protocol (802.11.x, 802.15.4, ISM modules) allows to tune the maximum TxPower
Processor CCLK	More and more processors allow to modify dynamically the processor core clock (or core voltage) that has important consequences on power
Sampling rate	In some application, sampling rate, and then processor wake-up, can be decreased without high consequence on application behavior
GPS Extinction Period (GEP)	When used to input a synchronization in the system, the GPS module can be turned off periodically
Wireless Emission Period (WEP)	Usually sensor transmit data when sampled. An alternative consists in imposing temporal periods to send buffers of data to network

Other degrees of freedom can be established according to the specific wireless system to improve. Additional examples can be provide for other systems: if sensor sampling rate is low (some hertz or lower), modern processors can be set in *deep sleep* state that ask for some μA ; modern processors internal voltage can also be adjusted to run only needed internal peripherals, etc. Author insist on the multiplicity of DOF that can be found even when wireless system seems to be already optimized.

Linking DOF to energy

Then, for each degree of freedom, the energy-variation law has to be defined according to DOF-variation. Depending on the control and the knowledge the WSN engineer has, laws can be defined analytically (e.g. by establishing a deterministic model) or by experimental energy measurements.

For PEGASE wireless platform, IFSTTAR team has leaded experimental campaigns to establish law for each identified DOF (WiFi TxPower, processor CCLK...). Above figures illustrate the empirical laws defined for two degrees of freedom: Wireless Emission Period (WEP) and GPS Extinction Period (GEP).

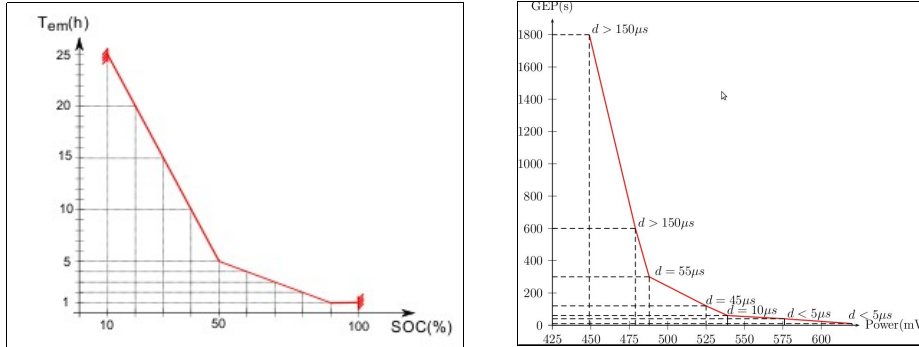


Figure 2. PEGASE Power consuming according to WEP (left) and GEP (right).

Figure 2.a is provided with a PEGASE whose WEP (WiFi emission) varies from every 1hour to 1 emission a day. Its consequence on power-consuming is given traduced in battery battery State Of Charge (SOC). WEP consequence on sensor behaviour only resides in sensor reactivity: data will be sent with more or less delay.

Figure 2.b gives the gain on PEGASE power-consuming from 0 to 150 mW when GPS extinction period varies from 40 to 1800s. For each selected period the consequence on time base drift (d) is given: from 5 to more than 150 μ S.

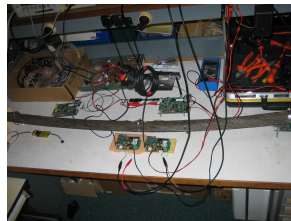


Figure 3. WSN evaluation benchmark for each and degree of freedom.

CONCEPT OF QUALITY INDEX

Once the degrees of freedom list and their laws are established, the second step consists in developing an analytical model of a *quality index*. This index is intended to be the acceptable variation on each degree of freedom without modifying original wireless sensor mission.

Here are listed examples that illustrate that definition: even if sensor sends data every 5 hours, it remains sampling and analysing; even if wireless TxPower is set lower, data transmission of closest nodes reach supervisor; even if GPS is set off during 5 minutes sensor time-base never drift more than 55 μ S, etc.

Two kind of analytical model can be determined: a theoretical global quality index which involves each degree of freedom and a quality index based on one parameter with many profiles.

Global quality index, one profile

The theory would ask that a global quality index is defined taking into account each degree of freedom. For example, the formula below explicit the quality index for only two DOF: Wireless Emission Period (WEP) and GPS Extinction Period (GEP).

$$Q_i = \frac{100 * (a_1 . tWEP_1 + a_2 . tWEP_2 + \dots + a_i . tWEP_i)}{tWEP_{tot}} * \left(\frac{(b_1 . tGEP_1 + \dots + b_i . tGEP_i)}{tGEP_{tot}} \right)$$

In above formula $tWEP_{tot}$ (or $tGEP_{tot}$) corresponds to the total WEP (or GEP) duration over 168h. With that modeling technique, user can set arbitrary $\{a_i\}$, $\{b_i\}$ coefficients to force and to balance the influence of each DOF variation on the quality of the wireless system. Quality Index vary from 0% to 100%.

This Quality Index (QI) formula should be extended for each identified degree of freedom. But, in spite of this global approach, even with few DOF, it becomes obvious that the result makes few sense; it is difficult to see in QI an intuitive wireless sensor behavior.

Single quality index, multiple profiles

A more realistic and comprehensible approach consists in defining a Quality Index dependent in only one parameter (e.g. one DOF) but for many “profiles”. Then a profile is intended to be a unique combination of others DOF whose values are set to arbitrary and relevant values.

For example, for PEGASE platform, the WEP degree of freedom has been retained as the unique QI parameter and 3 profiles have been defined. In our practical case is has been simplified as the ratio between the number of wireless emissions during one cycle (168h, e.g. one week), sensor is allowed to send data at a maximum of every hour.

$$Q_i = \frac{\text{Number of emission}}{\text{Max number of emission}_{168}}$$

Each profile corresponds to a realistic implementation choice:

- **Profile 1:** TxPower is maximum (26dB), CCLK is set to 500 MHz to perform complex (but optional algorithms), GPS module is always set on for synchronization, sampling rate is set to 250 kHz, a Led is on
- **Profile 2:** TxPower is medium (13dB), CCLK is set to 250 MHz, GPS is always on, sampling rate is set to 100 kHz, Led is off
- **Profile 3:** TxPower is set lower (7dB), CCLK is set to 250 MHz, GPS is set off during 5mn (and on during 40S), sampling rate is set to 100 kHz, Led is off

Linking quality index to power consumption

Then, behaviour of the system from energy point of view can be determined and represented as shown in above figure for each profile:

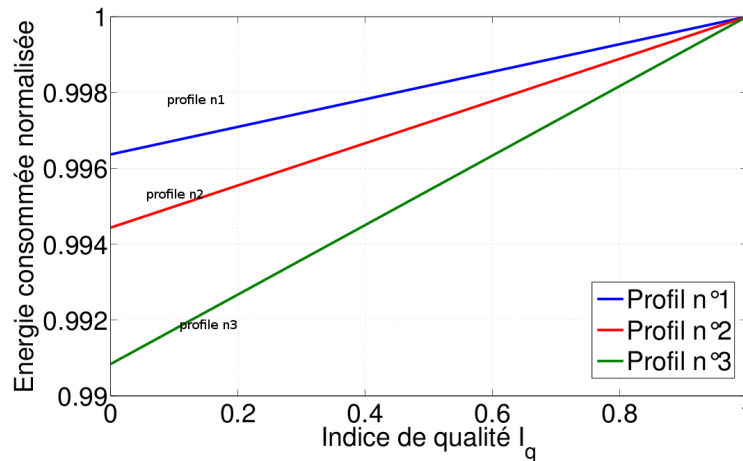


Figure 4. Energy-consumption according to profile and quality index.

To establish figure 4, the analyses made for DOF and law identification can be re-used. The result in Y-coordinate is given in energy normalized to the maximum energy that PEGASE system need: during profile n°1 with a quality index of 100% (e.g. 656 mW), in X-coordinate quality index is given from 0% to 100%.

OPTIMIZATION

A very benefit link between IFSTTAR and ENS-Cachan-SATIE Lab institute allowed to make the optimization task [4]. This optimization task has the double objective to minimize the both terms of Fsize that is the sum of the solar cell surface and the battery capacity.

$$Fsize = Spv + \gamma.Cbatt$$

Initial hypothesis

Initial values and dimensioning hypothesis would be too long to be described and justified here in detail, but, main hypothesis are following: typical solar cell surface from a polycrystalline technology fixed in middle France, the battery is a lithium-ion 12V module, maximum dimensioning are made for profile 1 on the worst week of the year (statically fewest sunny during 168h).

Pareto fronts

Associated ENS-Cachan SATIE team applied a specific optimizing algorithm [5] (under Matlab) that delivered Pareto diagrams. Those diagrams are particularly relevant when applied in optimal dimensioning: they do not give an optimal solution but the equilibrium between two parameters.

In this specific study, above figures give Pareto fronts. For each resulting optimization, profile (1, 2 or 3) and quality index (0.4 to 1) are set, then the optimization is performed.

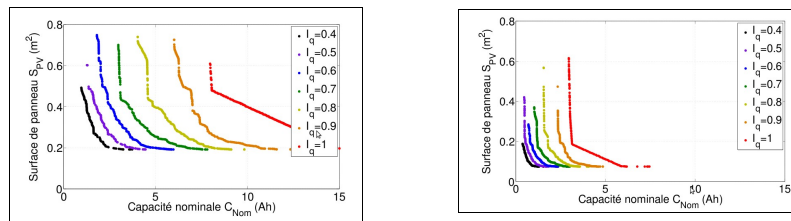


Figure 5. Pareto diagram for profile 1 and 3 and for various QI.

RESULTS

As mentioned above, the whole method has been applied to PEGASE use case. First, many degrees of freedom has been identified. Each of them have been evaluated independently from each others to determine its energy-law in the system. Then the 3 above profiles have been determined. This first step has highlighted that PEGASE power consumption can be improved from 656mW to 297 mW.

Physical implementation – A ready-to-use daughter board for PEGASE

Based on this theoretical method, its optimization results and experimental validations made step by step, IFSTTAR could design a specific daughter board to be added to the generic PEGASE platform [2].

The main mission of this daughter board is to ensure PEGASE autonomy. All functionalities referring to energy are delegated to this board:

- To offer a parametric implementation according to application solar cells and battery dimensioning
- To extract the maximum power from solar cell (or other source)
- To manage battery state of charge (accordingly to battery characteristics)
- To answer PEGASE request and to set it off in case of emergency

That “power manager” daughter board has been designed around an ATmega8 processor that runs all specific algorithms (user input parameters, battery charge respect, answer to PEGASE request...), a SEPIC sub-circuit ensure battery charge, an MPPT sub-circuit ensure maximum power point tracking from solar cell.



Figure 6: Physical implementation: a power manager daughter board

The final result will make generic PEGASE platform absolutely adaptable to any use-case where energy needs could vary. For the specific acoustic use-case, method implementation coupled to the functionalities of the “power manager” daughter board make the system could decrease its power need from 656 mW (profile: 1 QI: 100%) to 297 mW (profile: 3, QI: 100%).

Then, Pareto fronts diagrams, allowed to retain an optimal solution for profile n°3 and a QI of 80% with a lithium-ion battery of 2500 mA.h and only 0.5 m² of polycrystalline solar cell. In that fully acceptable case, a QI of 80% implies to differ wireless communications to an average drift of 2 hours a day between the moment data are transmitted to supervisor from the moment data has been recorded.

CONCLUSION

Present article paves the ground of a potential modest but new approach in Wireless Sensor and embedded system design in view of energy improvement. Even when systems are originally optimized and even if given PEGASE use-case is subject to improvements, the first step is helpful to identify system's degrees of freedom.

Once degrees of freedom have been determined, their law to energy have to be established; this can easily achieved by experimental quantifications.

The quality index concept is more difficult to understand when modelled for all degrees of freedom but, thanks to ENS SATIE laboratory, the proposed profiling method makes more sense. Each system profile correspond to a specific practical and state of the system and only one parameter influence system power-consumption.

Then computed optimizations let user makes its dimensioning choices: battery and solar cell sizes, quality index level, profile.

Once that work achieved IFSTTAR could design a specific daughter board dedicated to battery optimum charge control to make PEGASE running autonomously. This work is actually under validation; winter period reminds to be validated. In a perspective of improving system, a dynamic profiling algorithms is regarded to make the system able of changing dynamically its behaviour when energy availability is not a constraint. This evolution would consolidate the aim of this article: improving energy dimensioning of wireless sensors and moving them in auto adaptive systems.

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