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# Towards Persistent Structural Health Monitoring Through Sustainable Wireless Sensor Networks

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***Abstract*— this paper documents the design, implementation and characterisation of a wireless sensor node (GENESI Node v1.0), applicable to long-term structural health monitoring. Presented is a three layer abstraction of the hardware platform; consisting of a Sensor Layer, a Main Layer and a Power Layer. Extended operational lifetime is one of the primary design goals, necessitating the inclusion of supplemental energy sources, energy awareness, and the implementation of optimal components (microcontroller(s), RF transceiver, etc.) to achieve lowest-possible power consumption, whilst ensuring that the functional requirements of the intended application area are satisfied. A novel Smart Power Unit has been developed; including intelligence, ambient available energy harvesting (EH), storage, electrochemical fuel cell integration, and recharging capability, which acts as the Power Layer for the node. The functional node has been prototyped, demonstrated and characterised in a variety of operational modes. It is demonstrable via simulation that, under normal operating conditions within a structural health monitoring application, the node may operate perpetually.**

## I. INTRODUCTION

The application of wireless sensor network (WSN) technology to structural health monitoring (SHM) has the potential to provide a substantial and quantifiable improvement to existing monitoring solutions for civil infrastructure, the construction industry, and beyond. SHM has become a requirement for the vast majority of structure types in civil engineering resulting from a number of contributing factors, including the following: 1) new emergent methods of risk analysis, 2) the continual decline in acceptance by modern society to unneccessary, or potentially avoidable, risk-taking, and 3) the need to ensure the longevity of existing structures (with respect to reduced maintenance costs and improved safety). Wired systems exhibit costly deployment/installation periods, limited mobility considering redeployment, and, in some instances, maintenance on the wires themselves. Wireless solutions are attractive to SHM practitioners, as installation and redeployment costs may be significantly reduced, with mitigation provided against other potential hazards or difficulties (for example, retro-fitting an existing structure with SHM capabilities, or machinery on a construction site damaging cables used for SHM, respectively). Upon careful examination of the state-of-the-art SHM solutions exploiting WSN technology, it is evident that there exists the need for continued research and development at the platform level, such that a long-lasting, high-quality solution that meets, or exceeds, practitioner requirements can be developed and realised. To this end, the current art, and related work, is carefully examined in Section II.*A*, with respect to wirelessly enabled SHM solutions, and II.*B*, considering sustainable and smart power systems for WSNs.

It is the objective of the Green sEnsor NEtworks for Structural monItoring (GENESI) project [1] to develop a wireless sensor network enabled solution for the SHM market that is flexible to a range of potential deployment scenarios; is robust; delivers best available quality of service; and offers significantly enhanced lifetime (extending to decades). In order to achieve these goals, a bottom-up approach has been taken. The platform and emergent hardware architecture is presented in Section III, wherein a brief discussion of the rationale behind the abstraction, constituent components and fundamental enablers is presented.

Considering the bottom-up approach undertaken, delivery of a final platform is an iterative process. This is advantageous from a number of perspectives. It allows for experimentation with hardware configurations and component selection, permitting the identification and rectification of weaknesses, and facilitating the inclusion of optimal components as they become available; thus providing opportunities to benchmark subsequent embodiments. Importantly, it allows for relevant models to be created. In particular, the requirement exists to generate an accurate energy model capable of characterising the expected longevity of a proposed WSN based SHM (GENESI) solution. In order to develop the model, it is a requirement that the platform's energy characteristics are profiled in the various modes of operation expected within a functional deployment. To facilitate this objective, the hardware platform energy characteristics were investigated and evaluated. Presented in Section IV are the results of this investigation.

Further to the results presented, opporunities to further improve the platform are discussed in Section V, presented as caveats in the context of this contribution. Finally, a conclusion and discussion of ongoing and future work are presented in sections VI and VII, respectively.

## II. Related Work

The application of wireless sensor network technology to structural monitoring is not a novel endeavour. There exist many examples in the literature of proposed and deployed systems that attempt to exploit the expected synergy between wirelessly networked sensors and SHM. The most prevalent limitation to-date, and in WSN and ubiquitous computing at large, has been the availability of sufficient power to realise successful and persistent deployments, and is widely reported in the literature.

It is within the scope of the GENESI project to consider all relevant aspects of a successful system, including communications and networking protocols, quality of service, remote network reprogramming, querying, in-network processing, reasoning, data aggregation, adaptive sampling, etc.; however, these considerations are beyond the scope of the work presented in this contribution.

It is important, however, in the design of an appropriate hardware solution, to maintain an acute awareness of the eventual performance requirements and each of the tasks that it will be required to perform "in the wild". As such, the focus of the succeeding literature survey is two-fold. Firstly, the hardware proposed or implemented for a variety of similar application deployments are considered and contrasted with the proposed GENESI solution (*A*), and secondly (*B*), the emerging smart power solutions for wireless sensor networks are taken into consideration.

### *A. Wireless Structural Health Monitoring*

Lynch and Loh (2006) [2] provide an excellent summary review of the state-of-the-art in wireless structural health monitoring (WSHM) up to 2006. Historic (beginning mid-1990s) academic sensing solutions applicable to SHM are charted, in addition to a range of commercially available "motes" (the most recent and well-known in this case being the MICA2); and are comparatively evaluated, concluding that the potential does exist for widespread adoption of wireless SHM solutions provided that the limitations of heterogeneity and finite energy resources could be overcome to allow for extended periods of functional operation, citing the potential to utilise EH mechanisms to enhance functional longevity.

Pakzad *et al.* (2008) [3] briefly review the existing art of WSHM prior to presenting a deployed 64-node wireless structural monitoring system applied to a long-span (the famous Golden Gate) bridge. From a hardware perspective, the system uses only 4 MEMS accelerometers and a temperature sensor interfaced with the MICAz platform. This platform was chosen due to favourable trade-offs between computation and communication, and power consumption. Interestingly, it was noted that the sensor board consumed twice the power of the mote, resulting from a design decision to use a single power regulator for the node. It was concluded that in order for a future real-time, responsive, wireless SHM system to be realised: the operating system should support multi-threading to avoid delays of tasks during sampling, and a second microcontroller should be included to manage only sampling, with the added benefit of parallel computing (for simultaneous communication/processing).

Harms *et al.* (2009) [4] present the latest iteration of the SmartBrick platform. This platform utilises the ZigBee specification for in-network communication, enabled through the implementation of the CC2480 transceiver (updated from the CC2430 used in previous embodiments) and controlled using a TI MSP430 microcontroller. The device is designed to accommodate a number of analog and digital sensor interfaces, thus ensuring that a large range of sensor types may be supported. The authors note three potential power sources for the platform: alkaline and rechargeable batteries, and/or renewable sources, such as a solar panel.

Ceriotti *et al.* (2009) [5] present a WSN deployment for the monitoring of heritage buildings at Torre Aquila. The hardware implemented, customised 3MATE! nodes – available from [6] – similar to the Tmote/TelosB, inclusive of TI MSP430 microcontroller and CC2420 radio transceiver, are described, in addition to the node types required for the deployment. These include environmental (temperature), deformation (*ad hoc* fiber optic sensor), acceleration (tri-axial MEMS accelerometer) and sink (WiFi enabled Gumstix) nodes. The worst case scenario for functional longevity using one pair of size C batteries noticed the death of a node after 3.2 months, estimating the overall system lifetime to extend beyond one year.

### *B. Smart Power Systems for Wireless Sensor Networks*

The literature related to power supply for wireless sensor networks concerns the use of EH and various storage devices such as batteries (commonly Li-ion, rechargeable) and super-capacitors [7]. Energy harvesting (EH) systems can be categorized by energy storage devices and the types of ambient power sources.

Further to the aforementioned storage mechansims, electro-chemical fuel cell (FC) technologies, that use fuel (hydrogen, for example) to generate electrical power, are being considered due to their higher energy densities (comparable with batteries). In [8], the authors describe a fuel cell and battery hybrid (FC-Bh) system for use in portable microelectronic systems, characterising and analysing the performance of the system.

Considering the various ambient power sources, the most commonly used are photovoltaic, wind turbine or mechanical energy harvesting from vibrations or strain [7,9,10,11,12,14]. It is noticeable that very few projects have incorporated multiple energy resources in a single power unit, or platform. The system in [12] describes a reconfigurable energy subsystem for WSN, inclusive of solar and vibrational energy scavenging with Li-ion rechargeable batteries and super-capacitor for storage; one of the main features being flexibility and the option to select and fit the node *in* situ, in a Plug-and-Play manner.

The Ambimax system developed at the University of California [10] is a viable alternative, combining energy harvesting from wind and solar sources, again using batteries and supercapacitors for storage. This system has the added value of being able to perform maximum power point tracking (MPPT). In [14], Kheng and Panda present a hybrid device with indoor light and thermal harvestering. This is a good solution, architecturally similar to the GENESI unit, including an additional MSP430 only to perform MPPT. There is no possibility to recharge Li-ion batteries, or use FC technology. In addition, the system supplies the node without provision to exchange status information as the GENESI unit does. Finally, in [11] the authors present an interesting power unit with three environmental energy scavengers used to recharge NiMh batteries. The limitation in this case is that the storage pack cannot be changed and the power unit provides very little information relating to the status of its constituent components.

## III. The GENESI Platform

The first prototype of the GENESI platform for WSN enabled SHM is presented. The platform can be abstracted into three functional layers (Sensor, Main and Power) as illustrated in Fig. 1. This eases concurrent development, as iterative enhancements to each functional layer can be autonomously developed without impacting other layers.

For the purposes of GENESI pilot deployments, two test sites have been identified. The first is a bridge (*Pont de la Poya*), under construction in Freiburg, Switzerland; the second is a metro tunnel under construction in Rome (*Metropolitana Linea B1 Roma*). In collaboration with expert geomonitoring end-users, a suite of sensors suitable for the long term monitoring of the bridge has been established, in addition to the identification of the relevant strain and temperature guages necessary for the metro deployment. The sensors chosen are of the "off-the-shelf" variety, known and trusted within the SHM community.

An *ad hoc* sensor interface board is under development which will accommodate a variety of analog and digital sensor types, similarly to that presented in [4], with a range of add-ons. The complexity involved renders and in-depth desciption beyond the scope of this contribution, but will be published in due course. Additional components for inclusion in the "Sensor Layer" include enhanced ADC capability (with a minimum of 16-bit data resolution), additional flash memory (gigabytes – to meet a number of requirements), and some DC-DC conversion circuitry to supply sensors with higher operational voltage requirements. It is expected that some power dissipation is inevitable as a result, in the form of heat, which must be evaluated independently.

### A. Wireless Sensor Network Hardware

The first prototype of the GENESI main, or "mote", layer conforms to the stackable Tyndall 25mm form factor [13] (Fig. 2). The primary components of the layer are the MSP430F5437 microcontroller unit and the CC2420 radio transceiver. The decision to implement these components in the first prototype is reflective of the functionality and low-power characteristics of the microcontroller unit, comparable with other potential solutions, and the popularity of, and widespread support for, the CC2420 transceiver in the WSN community – and its perceived utility in future GENESI deployments. These initial design decisions were made in the abscence of the full suite of functional requirements for GENESI, but considered the state-of-the-art implementations of similar WSN deployments used for SHM.

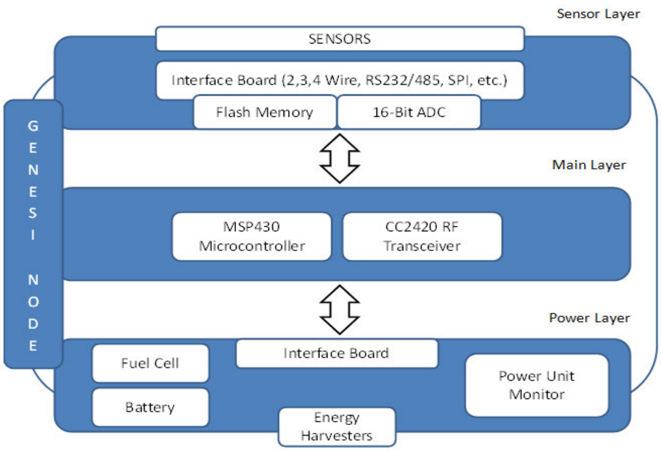


Fig. 1. GENESI Node v1.0 – layered hardware abstraction. Sensors for real deployments will be cabled through a suitable IP compliant enclosure for the node which must protect against moisture and impact (likely metallic). The Power Unit Monitor is realised as a secondary MSP430 MCU, capable of providing real-time power information, enabling true energy awareness

### B. Smart Power Unit

Fig. 3 illustrates the architecture of the Smart Power Unit, capable of hosting various environmental sources and storages (1/2 batteries, 1/2 supercapacitors and FC). The power unit is described as "smart" because it has been designed to provide advanced features, and the possibility to control and optimize operating parameters in the field. In particular it is possible to monitor the current state of the harvesters, batteries and micro fuel-cells. Furthermore, it is possible to change the operating frequency used by internal DC/DC converters and chargers.

The power unit uses the TI MSP430F2274 microcontroller, a 16-bit ultra-low power microcontroller, with 32KB flash, 1KB RAM, 10-bit ADC, 2 op-amp and 2 Universal serial communicator interfaces.

This device was chosen for ultra-low power consumption, coupled with the necessary ADC and peripherals for the development of the unit. The microcontroller can select the adequate power resources to guarantee the best power efficiency and can interact with the supplied devices improve the power management on both sides (power unit and supplied platform). The MCU execute programmable power management policies, and will provide the required flexibility and energy awareness, considering the node may be deployed in differing locations with varying environmental power availability.

The Smart Power Unit developed provides the following:

- Dynamic Maximum Power Point Tracking (MPPT). The power unit can decide to disable or to activate this

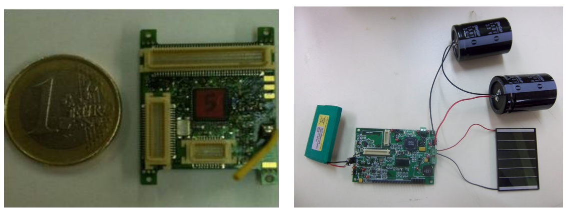

Fig. 2. Left: the GENESI v1.0 Main Layer prototype – with MSP430F5437 and CC2420 RF transceiver. Right: The Smart Power Unit prototype with solar EH, Li-ion rechargeable battery and supercapacitors.

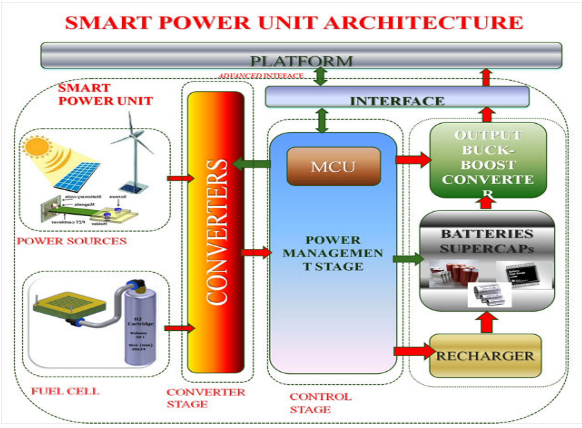


Fig. 3. Smart Power Unit Architecture – the interface to the Main Layer will be comprised of $I^2C$ and two GPIO to enable communication and interrupts, respectively.

feature. The presence of such a circuit is justified only if the power consumed to perform a Tracking of the Maximum power point is significantly less than the gained by MPPT on the energy transducer.

- Dynamic selection of the energy source used to recharge the reservoirs and supply the node.
- Dynamic alteration of the operating frequency and duty cycle. This capability serves to increase the efficiency of the energy conversion the power unit.
- Dynamic selection of storage. Increases efficiency of the power unit and extends cycles-lifetime of batteries. The unit can host two batteries, selecting one for charging and one for discharging, alternatively selecting the supercapacitor.

### C. *Novelty*

The GENESI platform is designed to exceed the state-of-the-art in wireless SHM from multiple perspectives. Primarily, the lifetime of the nodes, and therefore GENESI networks, is expected to significantly surpass any existing solution through combining the Smart Power Unit with low-power component and algorithm selection throughout the stack. The range of flexibility with respect to off-the-shelf sensor interoperation will exceed all known platforms. The ability to provide the required data resolution and associated QoS guarantees across a number of modalities has not yet been realised for exploitation by the SHM community. True energy-awareness, provided through Smart Power Unit interfacing (using $I^2C$ for regular communication and GPIO for hardware enabled interrupts) to the Main Layer allows for opportunistic sampling, and, potentially, networking, during periods of high ambient energy availability (and/or saturated storage facilities) will exceed the current art (to be examined and validated in future work). It is a design goal that the platform should remain operational for periods extending to decades to meet the requirements of long term SHM applications. Experimental results suggest that this target is not unrealistic, and are assessed in the following section.

## IV. Results

The prototyped platform has been evaluated experimentally with respect to operational power consumption. The approach is two dimensional. Firstly, the Main Layer is evaluated individually, in comparison with the TelosB platform (a similar mote in terms of constituent components, identical to the Tmote Sky). The results of this comparison are presented in Table I, below. It can be seen that the energy consumed by the layer outweighs that of the TelosB, which should not be the case considering datasheet values provided for each of the constituent components in varying modalities. The reasons for this have been identified and are under rectification. Through benchmarking the layer against a similar device, it was possible to debug the design, with fixes to be included in the next revision. The power consumption of the full GENESI v1.0 node in a number of operational modes was evaluated (presented in Table II). Secondly, MATLAB simulation was carried out in order to predict the power consumption of the entire node in a realistic deployment scenario.

### A. *Measured GENESI Node v1.0 Power Consumption*

The platform consists of a variety of active components. Energy consumers (e.g. sensors, MCU, etc.), energy providers (e.g. wind, solar, FC, etc.), and conversion circuitry (e.g. DC/DC, charger, etc.) coexist. The performance in terms of power consumption and energy availability are shown in the following tables (Table II and Table III, respectively).

Table II considers energy consuming components, with varying modalities. For the purposes of early demonstration, the inclinometer selected for the final deployment was interfaced with the GENESI node (sampled using PWM), illustrated in Fig. 4. It was shown to draw approximately 3mA during sampling. Table III details the power provided from different sources. Furthermore, energy lost through converter circuits is considered, and included in efficiency of single harvesting.

To evaluate the performance of solar harvesting, a $112cm^2$ PV module (max 450mW) was used, with an irradiation that forces the solar cell to produce about 50mW. A measure of the efficiency with MPPT recharging both a supercapacitor and Li-Ion batteries was taken. A plastic four-bladed horizontal-axis wind turbine, with a diameter of 6.3cm with a max 10mW output has been used as wind generator.

To evauluate the performance, the same assumption as in previous work [15] is used; measuring the power whilst recharging a 50F supercapacitor using a small fan as a transducer (airflow speed 16 km/h approx.), with a turbine diameter of 6.3cm.

TABLE I
MEASURED POWER CONSUMPTION: TELOSB VERSUS GENESI MAIN LAYER

| | **Measured Power Consumption** | |
|---|---|---|
| **Operational Mode** | **TelosB** | **GENESI Main Layer** |
| AM (TRX Off) | 2.15 mW | 5.78 mW |
| LPM3 | 17.82 µW | 90.09 µW |
| AM + TX (0dBm) | 60.06 mW | 62.37 mW |
| AM + TX (-25dBm) | 31.68 mW | 31.68 mW |
| AM + RX | 66.66 mW | 72.6 mW |

CURRENT DRAWN DURING VARIOUS MODALITIES WAS MEASURED USING A DATA LOGGER AND VOLTAGE DROP ACROSS A SHUNT RESISTOR, WITH POWER CONSUMPTION CALCULATED ACCORDINGLY. THE MCU WAS CLOCKED AT 8MHZ FOR ALL EXPERIMENTS.

TABLE II
GENESI NODE V1.0 POWER CONSUMPTION

| Devices | Consumption mW (3.3V) | | |
|---|---|---|---|
| | Active (mW) Measured | Active (mW) Simulation | Sleep (mW) |
| Main Layer (AM) | 5.78 | 10 | <1 |
| Sensor | 9.9 | 10 | <1 |
| Radio Tx | 56.59 | 55 | <1 |
| Radio Rx | 66.82 | 60 | <1 |
| MCU SPU (1Mhz) | 1.29 | 1 | 0.005 |

THE MCU OF MAIN LAYER WAS CLOCKED AT 8MHZ FOR ALL EXPERIMENTS. THE MCU OF SMART POWER UNIT WAS CLOCKED AT 1MHZ

TABLE III
ENERGY SOURCES: PERFORMANCE OF HARVESTERS AND FUEL CELL

| Sources | Performance | |
|---|---|---|
| | Max Power | Efficiency |
| Solar (Li-Ion Battery) | 450mW | 82% |
| Solar (SuperCap) | 450mW | 75% |
| Wind (SuperCap) | 10mW | 85% |
| FC (Li-Ion Battery) | 1W (recharging limit @ 200mA) | 80% |

THE EFFICIENCY WAS EVALUATED AS THE MEASURED POWER (V*I) OF SOURCE ON THE INPUT OF POWER UNIT AND THE POWER TRANSFERRED TO THE ENERGY STORAGE. THUS THE EFFICIENCY COUNTS BOTH ENERGY LOST FROM CONVERTER STAGES AND FROM SMP MCU.

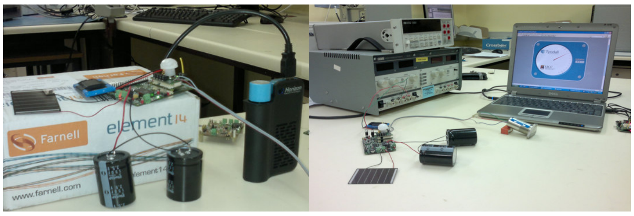

Fig. 4. Left: Fully integrated GENESI Node v1.0 Prototype. Right: Demonstration of integrated node sampling the inclinometer, communicating wirelessly with a sink node. For the purposes of demonstration, the Contiki OS is used to facilitate communication (Rime stack), with data visualisation through Labview.

Finally to evaluate the performance of recharging batteries from fuel cells, the industrial MiniPAK from Horizon was used [16]. The output of this device is 2W (5V, 400mA). This device can host a solid state hydrogen cartridge, called HYDROSTICK, which provides about 12Wh of energy. Measurements have been performed setting 200mA as max recharging current, because it is a correct trade-off between stability of the FC and time to recharge the battery (about 2.5 hours for 800mAh). In this case the efficiency is calculated as the power going out of the MiniPAK on the power incoming in the battery.

### *B. MATLAB Simulation*

In order to evaluate the performance of the approach and the lifetime of the platform, MATLAB simulation was employed. For simplicity, assumed is a system with just one 800mAh Li-Ion battery, a Horizon FC and solar panel. Energy intake from the energy harvester and solar light intensity over five days was measured (Fig. 5). All results relating to the measurement of aforementioned power and solar energy was stored and used as input for these simulations. Moreover, according to tests conducted, it is reasonable to assume that the FC may recharge the 800mAh battery 4 times, and supply the node when the battery level falls below 10% of battery capacity. The recharging time is fixed at 2.5 hours.

Table IV shows the different duty cycles used to evaluate the power consumption of the node in different conditions. The duty cycle (D) of the node's activity is defined as the fraction of time when the node is in an active state:

$$D = t_{on} / T \quad (1)$$

$$T = t_{on} + t_{off} \quad (2)$$

where T is the period, $t_{on}$ is active time and $t_{off}$ is inactive. Furthermore the sensor node must be active long enough for the sensor to wake/warm up ($t_{wakeup}$) and to acquire the measured data ($t_{acquire}$):

$$t_{on} >= t_{wakeup} + t_{acquire} \quad (3)$$

According to the functional requirements of the GENESI pilot deployments, the platform needs to collect data from sensors in normal mode 4-8 times per day and send them 1 time per day. Values $t_{on} = 4.5s$ (reasonably accurate due to warm up requirements, for example) for acquiring sensor data and $t_{on} = 4.5s$ for radio activities are used. Empirical evaluation suggests these times are sufficient to wake the node, sensor, and to perform acquisition. It is similar for radio activities; such as synchronization, information transfer, etc. Thus, a duty cycle of 0.05% with $t_{on} = 10s$ from (1) and (2) means T = 9000s and $t_{off} = 8995.5s$, and the node will acquire data every 2.5 hours; enough to collect almost 10 samples per day, satisfying the requirements. Also simulated are critical and alarm scenarios (as required by end-users), defined in Table IV, which require higher frequencies of sampling, data acquisition and information transmission.

Fig. 6 illustrates that, under these conditions, the GENESI platform is capable of working perpetually both in *normal mode* and in *critical mode*. Furthermore, the simulation shows that in *alarm mode* the battery can provide energy if the harvester is not collecting enough energy. Whilst the main aim of FC is to avoid this situation and to recharge the battery when it is almost empty, it may be used to power the system

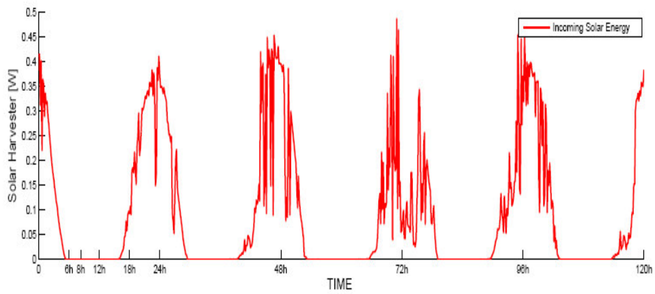


Fig. 5. Solar energy harvested during five consecutive days using the PV panel

TABLE IV
MODALITIES SIMULATED

| SCENARIO | DUTY CYCLES | | | SAMPLING |
|---|---|---|---|---|
| | *Node* | *Radio (Tx=Rx)* | *Sensor* | |
| Critical | 0.35% | 0.35% | 0.35% | 3 per hour |
| Alarm | 0.75% | 0.75% | 0.75% | 6 per hour |
| Normal mode | 0.05% | 0.05% | 0.05% | 10 per day |

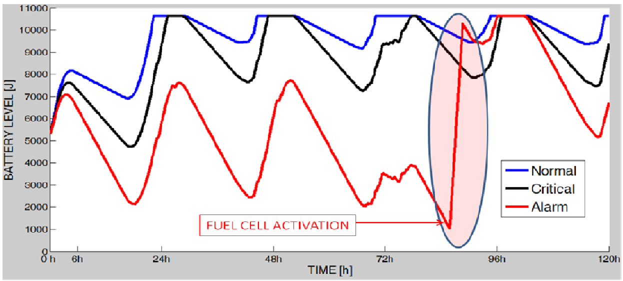


Fig. 6. Simulated battery levels for functional modalities

directly. Using this configuration, it can be stated with reasonable confidence that the platform will survive for several days in very critical situations, which usually would not persist for more than a few days.

## V. Caveats

Simulation is carried out using EH information from the solar panel as tested in Bologna, Italy, over a five day period. This cannot be considered a valid reflection of realistic conditions for a number of deployment scenarios (i.e. the metro tunnel pilot deployment for GENESI), varying geographical locations, or seasonal shifts. It will be necessary to perform a full field trial to validate precise measurements for longevity based on the implementation described above. It is expected that further improvements with respect to overall power consumption of the node can be achieved. It is likely, however, that the radio transceiver implemented in v1.0 will be upgraded to the CC2520 for the next version of the platform. This design choice relates to marginally improved power consumption, improved wake-up time, and compliance with the 2006 revision of the IEEE 802.15.4 standard. Furthermore, it will be necessary to include all of the active components of the Sensor Layer, once complete, however insignificant the impact may be with respect to the overall power consumption of proposed platform.

## VI. Conclusion

Described were the design, implementation and characterisation of a prototype wireless sensor node suitable for the long term monitoring of structural health, as applicable to a number of deployment scenarios. Considering the breadth of previous research effort to provide a solution that does not suffer from premature node death, the primary focus has been on implementing the lowest cost solution with respect to power consumption, supplemented through a smart power provision mechanism. The node architecture presented is novel, considering both the provision of real time power information to the sensor node, integration of interoperable EH mechanisms with multi-storage and electrochemical fuel cell technology. The platform will allow for novel research directions to be undertaken in terms of energy-aware protocol design, opportunistic sampling and networking, among others.

## VII. Future Work

In addition to resolving the concerns highlighted in Section V, thus realising the next generation of the GENESI Node, additional consideration must be given to the design of the physical enclosure, for which there are a significant set of requirements. End-to-end data transfer will require the realisation of a gateway node (similar to the sink node presented in [5]) with wired (Ethernet) and wireless (UMTS/LTE) connectivity to the IP backbone, thus allowing seamless integration with existing end-user back-end systems. To-date, primary consideration has been given to power consumption considerations with respect to the design of the node. Another equally important consideration for SHM is quality of service. Future work will involve characterisation of the hardware focussing on the delivery of appropriate levels of QoS for the SHM community.

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## References

[1] (2010) GENESI: Green sEnsor NEtworks for Structural monItoring. [Online]. Available: http://genesi.di.uniroma1.it/

[2] J. P. Lynch and K. J. Loh, "A Summary Review of Wireless Sensors and Sensor Networks for Structural Health Monitoring", *The Shock and Vibration Digest*, vol. 38, no. 2, pp. 91-128, 2006.

[3] S. N. Pakzad, G. L. Fenves, S. Kim and D. E. Culler, "Design and Implementation of a Wireless Sensor Network for Structural Monitoring", *Journal of Infrastructure Systems*, vol. 14, no. 1, pp. 89 - 101, 2008.

[4] T. Harms, B. Banks, S. Sedigh Savestani and F. Bastianini, "Design and Testing of a Low-Power Wireless Sensor Network for Structural Health Monitoring of Bridges", *in Proc. Vol. 7292, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems.* March, 2009.

[5] M. Ceriotti, L. Mottola, G. P. Picco, A. L. Murphy, S. Guna, M. Corra, M. Pozzi, D. Zonta and P. Zanon, "Monitoring Heritage Buildings with Wireless Sensor Networks: The Torre Aquila Deployment", *in IPSN 09*.

[6] 3TEC S.r.l. (2010) 3MATE! 2.4GHz IEEE 802.15.4 WSN MODULE. [Online]. Available: http://www.3tec.it/

[7] X. Jiang, J. Polastre and D. Culler, "Perpetual environmentally powered sensor networks", *in: Proc. of IEEE Workshop on Sensor Platform, Tools and Design Methods for Networked Embedded Systems (SPOTS),* Los Angeles, CA, USA, April 2005.

[8] K. Lee, N. Chang, J. Zhuo, C. Chakrabarti, S. Kadri, and S. Vrudhula, "A fuel-cell-battery hybrid for portable embedded systems," *ACM Trans. Des. Autom. Electron. Syst.*, vol. 13, pp. 1-34, 2008.

[9] R. Torah, P. Glynne-Jones, M. Tudor, T. O'Donnell, S. Roy and S. Beeby, "Self-powered autonomous wireless sensor node using vibration energy harvesting", *Meas.Sci.Technol.* **19** (125202) (2008)

[10] C. Park and P. Chou, "AmbiMax: autonomous indoor energy harvesting platform for multi-supply wireless sensor nodes," *in Proc. SECON 2006*, Reston, VA, 2006, pp. 168-177

[11] R. Morais, S. G. Matos, M. A. Fernandes, A. L. G. Valente, S.F.S.P. Soares, P.J.S.G. Ferreira and M.J.C.S. Reis, "Sun, wind and water flow as energy supply for small stationary data acquisition platforms", *COMPUT ELECTRON AGR*, vol.64, no. 2 (2008) pp. 120-132.

[12] A.S. Weddell, N.J. Grabham, N.R. Harris and N.M. White, "Modular Plug-and-Play Power Resources for Energy-Aware Wireless Sensor Nodes", *in Proc. SECON 2009*. Piscataway, NJ, USA, 422-430.

[13] S. J. Bellis, K. Delaney, B. O'Flynn, J. Barton, K. Razeeb and C. O'Mathuna, "Development of field programmable modular wireless sensor network nodes for ambient systems", *Computer Communications,* 28 (2005), pp. 1531-1544.

[14] Y.K. Tan and S.K. Panda, "Energy Harvesting from Hybrid Indoor Ambient Light and Thermal Energy Sources for Enhanced Performance of Wireless Sensor Nodes", IEEE Transactions on Industrial Electronics, vol.58, in-press, 2011.

[15] D. Carli, D. Brunelli, D. Bertozzi, and L. Benini, "A high-efficiency wind-flow energy harvester using micro turbine," *in Proc. SPEEDAM'10*, Jun. 14–16, 2010, pp. 778–783.

[16] Horizon Fuel Cell Technologies Pte Ltd (2010) Introducing the MiniPAK "Personal Power Center". [Online]. Available: http://www.horizonfuelcell.com/electronics.htm