Battery-free Structural Health Monitoring System for Concrete Structures

Gaël Loubet, Alassane Sidibe, Alexandru Takacs, Jean-Paul Balayssac, Daniela Dragomirescu

To cite this version:

Gaël Loubet, Alassane Sidibe, Alexandru Takacs, Jean-Paul Balayssac, Daniela Dragomirescu. Battery-free Structural Health Monitoring System for Concrete Structures. 13th International Workshop on Structural Health Monitoring, IWSHM 2021, Mar 2022, Standford, CA, United States. hal-03648195

HAL Id: hal-03648195

https://laas.hal.science/hal-03648195

Submitted on 21 Apr 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

COVER SHEET

Title:
Battery-free Structural Health Monitoring System for Concrete Structures.

Authors:
Gaël LOUBET
Alassane SIDIBE
Alexandru TAKACS
Jean-Paul BALAYSSAC
Daniela DRAGOMIRESCU

ABSTRACT

This paper presents a cyber-physical system based on a wireless sensor network dedicated to structural health monitoring of reinforced concretes throughout their lifetime. This cyber-physical system is intended to implement a communicating reinforced concrete. Two types of nodes compose this WSN. The sensing node is fully wireless, can measure various parameters (such as temperature, relative humidity, mechanical strain, or resistivity), is battery-free, and is wirelessly and remotely powered and controlled *via* a radiative electromagnetic power transfer system by the second type of nodes, the communicating node. The communicating node connect the WSN to the digital world.

INTRODUCTION

Wireless Sensor Networks (WSN) can be employed to deploy Cyber-Physical Systems (CPS), both by monitoring and/or controlling the physical world, and by connecting the physical and digital worlds. They are suitable for Structural Health Monitoring (SHM) applications in various fields, such as the civil engineering industry. Currently, one of the main limitations to the deployment of WSN is their energy autonomy. To overcome this bottleneck, ambient energy harvesting and Wireless Power Transfer (WPT) solutions are investigated [1].

In this context, the McBIM project (Material communicating with the Building Information Modelling (BIM)) [2], funded by the French National Research Agency (ANR), design and implement a CPS dedicated to the SHM for civil engineering industry. This one is composed of a WSN directly embedded in the reinforced concrete.

In this paper, the design and the implementation of the WSN embedded into the reinforced concrete will be presented. Its energy autonomy, its sensing capabilities, as well as its integration into reinforced concrete will be detailed.

Gaël LOUBET[1,2,3], Alassane SIDIBE[1,2,3,4], Alexandru TAKACS[1,2,3,5], Daniela DRAGOMIRESCU[1,2,3,6]; LAAS-CNRS[1], Université de Toulouse[2], CNRS[3], UWINLOC[4], UPS[5], INSA[6]; 7, Avenue du Colonel Roche, 31400 Toulouse, FRANCE.
Jean-Paul BALAYSSAC; LMDC, UPS, Université de Toulouse, UPS-INSA; 135, Avenue de Rangueil, 31400 Toulouse, FRANCE.

DESIGN AND IMPLEMENTATION OF COMMUNICATING REINFORCED CONCRETE

In order to make communicating the reinforced concretes, the choice has been made to embed a WSN with the ability to sense various parameters, to process, store and share wirelessly the collected data both with the physical and digital worlds. The aim of making it useful throughout its life -expressed in decades- and for each step of its lifecycle, the issues of energy autonomy, reconfigurability, measurement ability and accessibility have been considered.

Architecture of the Cyber-Physical System and its Wireless Sensor Network

The proposed WSN is part of a full CPS and has two kinds of nodes: the communicating nodes (CN) and the sensing nodes (SN) as shown in Figure 1.

The CN are organized in a mesh network, accessible and powered in a conventional way. They will collect, process, store and share together, as well as with the digital world and its virtual models (e.g. a digital twin) *via* the Internet, the data measured and sent wirelessly by the SN. Moreover, the CN will power the SN wirelessly over several meters.

The SN are organized in a star topology around a CN, inaccessible because randomly deployed and buried into the reinforced concrete, and autonomous in terms of energy by being battery-free and powered wirelessly by the CN. These must measure some parameters to quantify the health of the reinforced concrete and/or its environment, then pre-process and transmit wirelessly the collected data to the CN.

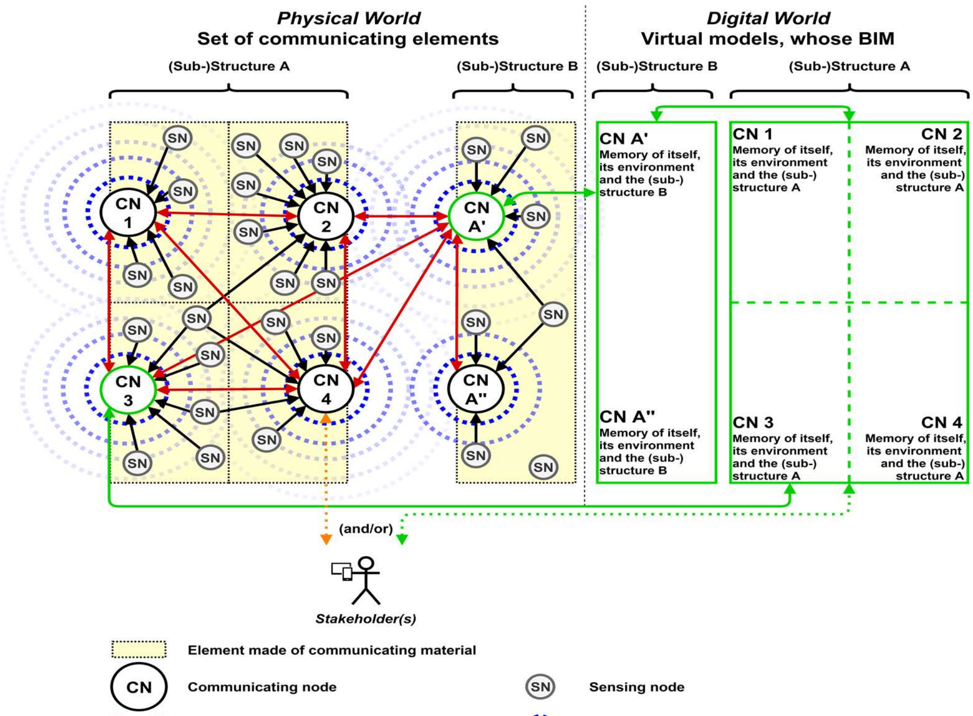

Figure 1. Architecture of the proposed cyber-physical system and its wireless sensor network.

The WSN is based on the long-range LoRa ultra-low power wireless communication technology, but experiments with the Bluetooth Low Energy (BLE) are in progress. The power supply of the SN by the CN is achieved by radiative electromagnetic WPT system operating in the far-field. Further details on the design and implementation of the nodes are available in [3, 4].

Long-Term Energy Autonomy of the Sensing Nodes

With the aim of making the SN energy autonomous in the long term (that says for decades), and because these are inaccessible once deployed (because buried into reinforced concrete), these are designed to be wirelessly powered in the far-field (up to several meters), battery-free, and able to cold-start.

Wired solutions have been ruled out in favor of wireless ones. The former require manual installation, are expensive and heavy, and are difficult to deploy on a large scale.

Due to slow evolution of monitor parameters (e.g. temperature, humidity, mechanical strain, corrosion rate, etc.), the frequency of measurement can be low (e.g. on an hourly, daily, or weekly base). That is why an energy "harvest and store, then use" strategy has been chosen. Due to the use of a Power Management Unit (PMU) commercially available, it is possible to manage only by hardware the power harvesting and the energy storage and use. Using the cold start capability of this PMU allows to start from an empty energy buffer. The SN can be kept functional for a long time, even if not used and supplied during a long period of time.

The choice of a (super)capacitor has been made for the energy buffer. Regardless the chosen wireless communication technology (LoRa, BLE, etc) and the sensing technology, a low to moderate capacity is needed to supply the SN in the targeted operation mode: "harvest and store, then use", with "use" consisting solely of the collection and transmission of data. Low power losses are sought. Long lifetime with a lot of charge and discharge cycles, as well as full discharge ability are needed for a long-term use. So, the batteries do not meet all these requirements: they have too high capacities, limited lifetime, as well as limited number of charge and discharge cycles and cannot be completely empty. The rechargeable ones require a recharge system, but today only wired or short-range wireless ones are available that forces the operators to know their location to recharge these, which is difficult, time-consuming and expensive.

The proposed choice is to use a far-field radiative electromagnetic WPT system to provide the required energy to the SN. This system is independent of the environment of deployment and its unavailable or fluctuating ambient energy sources [5] and of the targeted structure and application. Moreover, it has a sufficient range of use, and it is scalable in all civil engineering use cases. It provides a generic, long-range and long-term solution. The available near-field electromagnetic WPT solutions are limited in terms of range up to tens of centimeters.

Thus, due to its design based on battery-free SN supplied by a far-field WPT system, the proposed system can be used for decades, especially for SHM applications in civil engineering, whatever the environment and the targeted structure.

The CN are still not energy autonomous. But, it could be possible to use batteries to power these due to their accessibility. Few propositions have already been made to power with photovoltaic cells, both LoRaWAN gateways [1] and proof-of-concept radiative electromagnetic power sources [6].

Reconfigurability of the Sensing Nodes

The SN can be reconfigured on demand in terms of periodicity of measurement and data wireless transmission. The CN can remotely control and reconfigure the periodicity of functioning of the SN by tuning the WPT system, and thus by controlling the among of power available on each of them. This is a purely hardware-based solution that does not require any modification of the SN. This function can be improved by designing and implementing a beam-forming solution for the source of the WPT system. The global energy efficiency could be enhanced.

Measurement Capabilities of the Sensing Nodes

The SN have been designed in order to provide a generic platform on which various kinds of sensors can be connected. In order to limit the needs in terms of energy and computing capacity, only direct and temporally punctual measurements for non-destructive testing (NDT) methods have been considered. Methods requiring signal processing and/or energy-consuming equipment have been discarded. In the case of the monitoring of reinforced concretes during all their lifespan, several sensors have already been implemented and tested. These allow to get estimations of the temperature, relative humidity, mechanical strain and corrosion rate and thus, allow to monitor the curing process *via* the maturity method or the exploitation phase thanks to various measurements. By adding an identifier and by storing the data in the material, the traceability could be covered.

TEMPERATURE AND RELATIVE HUMIDITY SENSOR

Temperature and relative humidity sensors have first been implemented. The off-the-shelf Texas Instruments HDC20*0 sensors have been chosen for a temperature range from -40 °C to +125 °C and a relative humidity range from 0 % to 100 %, respectively with an accuracy of ±0.2 °C and 2 %.

Thermodiodes designed and manufactured by the University of Cambridge have been used as temperature sensors [7]. These are highly linear, accurate and very low-power. The subsidiary circuits (zero-temperature coefficient current source and scaling buffer circuit) have been designed with components that do not achieve the lowest possible power consumption. The proposed architecture provides a temperature range larger than from -30 °C to +125 °C, with an accuracy lower than ±0.16 °C, measurable on a voltage from 0 V to 1 V.

STRAIN GAUGE

As a simple and low-cost proof-of-concept, a naked linear strain gauge has been implemented and tested in a quarter Wheatstone bridge configuration to monitor the mechanical deformation. To increase the linearity and to decrease the power consumption, the bridge has been powered by a current source, whilst an amplifier and a scaling circuit has been used to get a measurement voltage between 0 V and 1 V. This cheap configuration must be improved to move beyond the proof-of-concept stage and to provide a more energy efficient and accurate system. This can be achieved by designing more precise electronic and sensor: multidirectional and/or in half- or full-bridge configuration and/or with a dedicated mechanical specimen to get a load cell.

RESISTIVITY SENSOR

In order to be able to estimate the corrosion rate, a resistivity sensor designed by civil engineering researchers from the LMDC lab has been implemented, as presented in Fig. 2. This is fully buried in the reinforced concrete sample under test and is based on a direct current driven Wenner probe, with four identical and equally spaced probes. A buffer circuit allows the measurement of a voltage. This first implementation must be improved to move beyond the proof-of-concept stage and to provide a more energy efficient and accurate system. This can be achieved by designing a more precise electronic and by considering other kinds of configuration, potentially with a larger number of probes. The periodicity of measurement has been assumed to be greater than two hours, and as the duration of the measurement is short, the polarization of the concrete has not been considered. However, to avoid this effect, an alternative current source can be employed at the cost of a more complex electronic.

Integration of the sensing nodes into the reinforced concrete

Currently, the choice has been made to cast all the SN into the reinforced concrete. This solution provides the highest security level, but reduces the wireless communicating range and available power, and results in longer (re)charging times. There are two alternatives: casting only the sensor in the core of the concrete and the rest on the surface; or casting the SN in the core of the concrete and its antenna on the surface. For the first, the SN are accessible, thus replaceable and updatable. For the second, the SN are inaccessible and the constraints of the electromagnetic propagation are released. In the two cases, measurements are performed at the most relevant locations, but the use of wires between the different parts can create mechanical weaknesses and access to the surface is also an access for pollutants and contaminants.

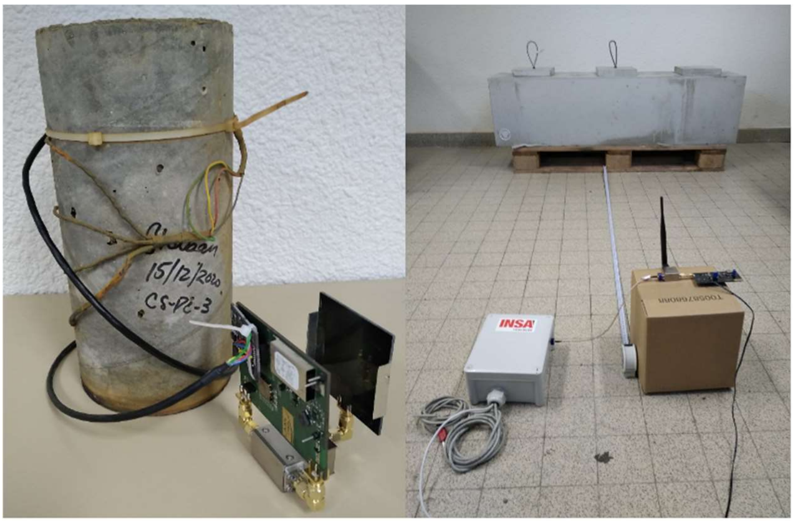

Figure 2. Photographs of: a sensing node with a resistivity sensor (left) and the experimental setup with sensing nodes embedded in a reinforced concrete beam (right).

EXPERIMENTAL RESULTS

Several qualitative and quantitative tests in several configurations have been carried out, as the one presented in Fig. 2 [3,4]. The SN is embedded in three 15 cm x 15 cm x 15 cm cavities of a reinforced concrete beam. The SN is powered and controlled wirelessly up to several meters by the CN.

According to Fig. 3, the SN need about 1.6 seconds to complete a full process: power-up, initialization, measurement, pre-processing, LoRaWAN transmission, regardless of the sensor and transmission power. The energy required is strongly correlated to the transmission power (about 92 mJ at +4 dBm and 172 mJ at +16 dBm), and little to the sensor (up to +7.5 mJ when using two thermodiodes simultaneously).

Regarding the WPT, the duration of the first charge from an empty energy buffer and of the recharges is function of the electromagnetic energy available at the input of the SN, as shown in Fig. 4. The radiated electromagnetic power is essentially function of the distance with the power source, the CN. In this case: 868 MHz and +33 dBm or 2 W EIRP, according to local regulations [8]. These times have been characterized between -14 dBm and +15 dBm, and are respectively about 34 h and 36 min for first charge and 1 min for recharge, and about 14 h and 38 min for first change and 30 s for the recharge.

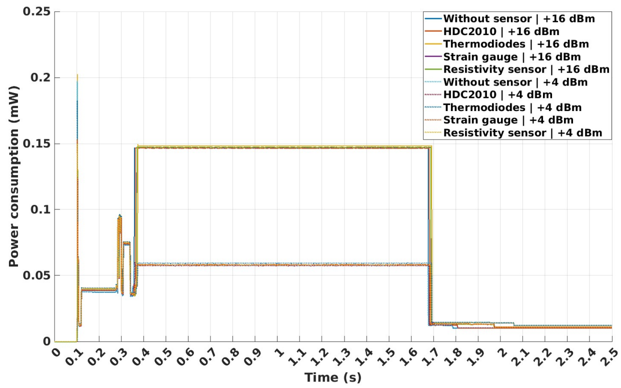

Figure 3. Power consumption of the sensing nodes against the sensor and the transmission power.

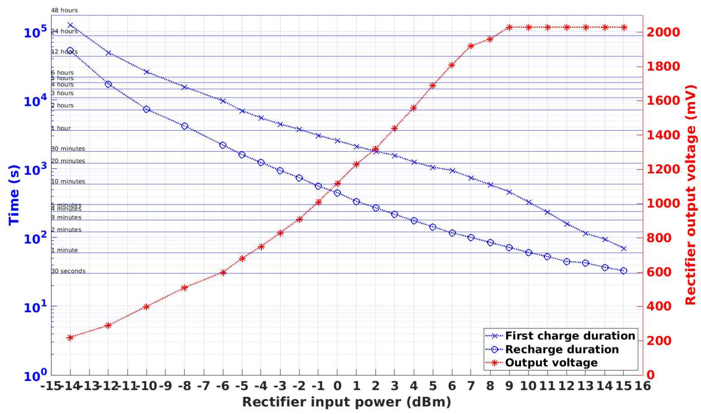

Figure 4. Durations of the first charge and recharges, and rectifier output voltage against the electromagnetic power applied at the input of the sensing node for a frequency of 868 MHz.

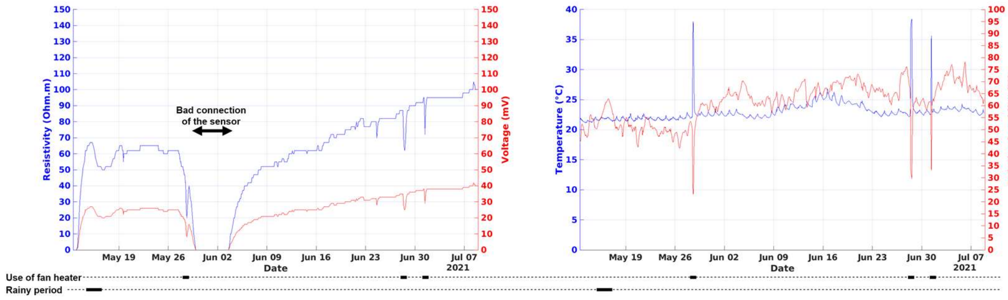

Figure 5. Evolutions of the computed resistivity and of the measured output voltage of the resistivity sensor, and of the temperature and relative humidity, for several days of concrete drying.

Fig. 5 presents a medium-term characterization of a concrete sample embedding a resistivity sensor driven by a SN and located in the neighborhood of another SN equipped with a temperature and relative humidity sensor. Even if this test has been carried out in the air and with a conducted electromagnetic power to be independent of the environment fluctuations, a consistent behavior can be observed during the drying process of the concrete, and a correlation between the environment parameters and the resistivity is highlighted (especially when a fan heater is used near the setup, but also with the day and night cycle or after a rainy period).

IMPROVEMENTS AND PERSPECTIVES

A full proof-of-concept of the targeted CPS has been achieved. Some parameters have still to be improved: the range of use that is limited by the WPT system and the regulations to several meters, currently about 11 meters; the global energy efficiency; the volume and the packaging of the SN.

Both the range of use and the energy efficiency can be increase, especially by improving the energy harvesting system by using a more efficient rectenna, a higher gain antenna, a PMU requiring less power, a low loss energy buffer and by using a power source generating optimized electromagnetic waves.

The energy efficiency can be also improved by reducing the energy needed by optimizing the sensor, the pre-processing and the wireless transmission protocol (for LoRaWAN: the data-rate, the payload).

The antenna is the main dimensioning element and it depends of the targeted performances (highest performances, bigger the antenna) and the environment (e.g. into or on reinforced concretes). A packaging to cast the WSN into reinforced concrete must be designed to protect it without altering its functioning.

CONCLUSION

This paper proposes an innovative SHM system, dedicated to the monitoring of reinforced concretes throughout their life, which can be easily adapted to various applications. This CPS is based on a battery-free WSN buried into reinforced concrete composed of low-cost wireless SN that can drive different types of sensors and are completely autonomous for decades. The Sensor Nodes are powered wirelessly by far-field radiative electromagnetic waves, and based on ultra-low power wireless communication technology. They are remotely reconfigurable in terms of periodicity of use (measurement and wireless communication) through the tuning of the power source used by the WPT system. It has to be noted that this is one of the first implementations of a resistimeter fully embedded into concrete [9], and the first fully wireless and battery-free.

ACKNOWLEDGMENT

This research has been funded by the French National Research Agency (ANR) under the McBIM project, grant number ANR-17-CE10-0014. The authors would like to thank all their French partners in the McBIM project: CRAN (Nancy), LIB (Dijon), and FINAO SAS / 360SmartConnect (Trans-en-Provence).

REFERENCES

1. Peruzzi, G., and Pozzebon, A. 2020. "A review of energy harvesting techniques for Low Power Wide Area Networks (LPWANs)," *Energies*, 13(13):3433.
2. Derigent, W., David, M., Wan, H., Dragomirescu, D., Takacs, A., Loubet, G., Roxin, A., Melet, R., and Montegut, L. 2019. "Materials communicating with the BIM: aims and first results of the McBIM project," *12th International Workshop on Structural Health Monitoring (IWSHM)*.
3. Loubet, G., Takacs, A., and Dragomirescu, D. 2020. "Implementation of a Wireless Sensor Network Designed to be Embedded in Reinforced Concrete," *46th Annual Conference of the IEEE Industrial Electronics Society, IECON 2020*, 2195-2200.
4. Loubet, G., Takacs, A., Gardner, E., De Luca, A., Udrea, F., and Dragomirescu, D. 2019. "LoRaWAN Battery-Free Wireless Sensors Network Designed for Structural Health Monitoring in the Construction Domain," *Sensors*, 19(7):1510.
5. Matiko, J.W., Grabham, N.J., Beeby, S.P., and Tudor, M.J. 2013. "Review of the application of energy harvesting in buildings," *Measurement Science and Technology*, 25(1):012002.
6. Georgiadis, A., and Collado, A. 2013. "Solar powered class-E active antenna oscillator for wireless power transmission," *2013 IEEE Radio and Wireless Symposium*, 40-42.
7. De Luca, A., Pathirana, V., Ali, S.Z., Dragomirescu, D., and Udrea, F. 2015. "Experimental, analytical and numerical investigation of non-linearity of SOI diode temperature sensors at extreme temperatures," *Sensors and Actuators A: Physical*, 222:31-38.
8. ETSI. 2014. "Electromagnetic compatibility and radio spectrum matters (ERM); short range devices (SRD) intended for operation in the bands 865 MHz to 868 MHz and 915 MHz to 921 MHz; guidelines for the installation and commissioning of radio frequency identification (RFID) equipment at UHF," *ETSI TR 102 436, V2.1.1*.
9. Corva, D.M., Hosseini, S.S., Collins, F., Adams, S.D., Gates, W.P., and Kouzani, A.Z. 2020. "Miniature resistance measurement device for structural health monitoring of reinforced concrete infrastructure," *Sensors*, 20(15):4313.