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Materials communicating with the BIM: results of the McBIM project

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Abstract: In 2010, the Research Center for Automatic Control (CRAN) proposed the concept of “communicating materials”, which led to this current project. Indeed, 3 French laboratories (the CRAN, LAAS and LIB) associated with one company (360SmartConnect/FINAO SAS) are working in the framework of the McBIM project to design a “communicating concrete”, made of concrete equipped with embedded low-energy wireless micro-sensors. This paper briefly describes the context of the McBIM project with the main research goal and objectives and then focus on the results in the different parts of the project regarding the different research issues, explored by the project.

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Keywords: Energy harvesting, Wireless Sensor Network, Digital Twin, Building Information Modelling, Product Lifecycle Monitoring, Interoperability.

1. INTRODUCTION

In 2010, a new paradigm was proposed in (Kubler et al., 2010), introducing “**communicating materials**”, i.e. materials able to communicate with their environment, process and exchange information, and store data in their structure. Besides, they also can sense their environment and measure their own internal physical states. Communicating materials are particular special types of intelligent products, a concept initially introduced in the manufacturing industry (McFarlane et al., 2003). In this concept, a product is a smart item with enhanced monitoring and decision-making capabilities (Meyer et al., 2009). Diverse early prototypes of communicating materials were designed (or simulated) **for the needs of the construction industry**, either via the use of RFID tags or self-powered wireless sensor networks (WSNs) embedded into the material (Kubler et al., 2012), (Mekki et al., 2015). Since communicating materials allow monitoring and tracing the product all along its lifecycle, we thus have defined the notion of “**Product Lifecycle Monitoring**” (Wan et al., 2020a).

This project called McBIM – for Materials communicating with the Building Information Modelling¹ – is funded by the French National Research Agency for the period 2018-2022. It regroups 3 French laboratories (the CRAN, LAAS and LIB) associated with one company (360SmartConnect/FINAO SAS).

¹ Interested reader may visit the McBIM website : <http://mcbim.cran.univ-lorraine.fr>

To realize this vision, these different partners investigate the following research issues:

Node design (LAAS): the wireless sensor network embedded into the concrete must be designed to communicate in a highly constrained and aggressive environment. Since the lifetime of a concrete element can be up to 50 years, relying only on non-rechargeable batteries or supercapacitors is not enough to ensure a sufficient availability of the embedded WSN. Innovative wireless energy harvesting techniques have been investigated and solutions proposed to design battery-free sensor nodes.

Network management (CRAN): different communicating concretes can be assembled in the same structure to form a global WSN. This type of structure eases data collection from the sensor nodes of all the concrete elements to a gateway node elected among the WSN. Depending on the network topology and the data collection periods, nodes will be differently solicited and consume more or less energy, which conditions their lifetime. To monitor and eventually reorganize these networks, this part of the project proposes energy consumption models able to support these dynamic networks.

Information Management (360SC): collected data are sent towards an external system designed to manage all the information concerning a communicating concrete. This information system may help to retrieve data related to an element (manufacturer, temperature) or a set of elements (average temperature of a group of elements, actual location). In this regard, an information management system has been

proposed to get and store measured data related to an element, with compatibility with BIM platforms. Moreover,

this system also manage data related to the sensor network (node residual energy, WSN structure).

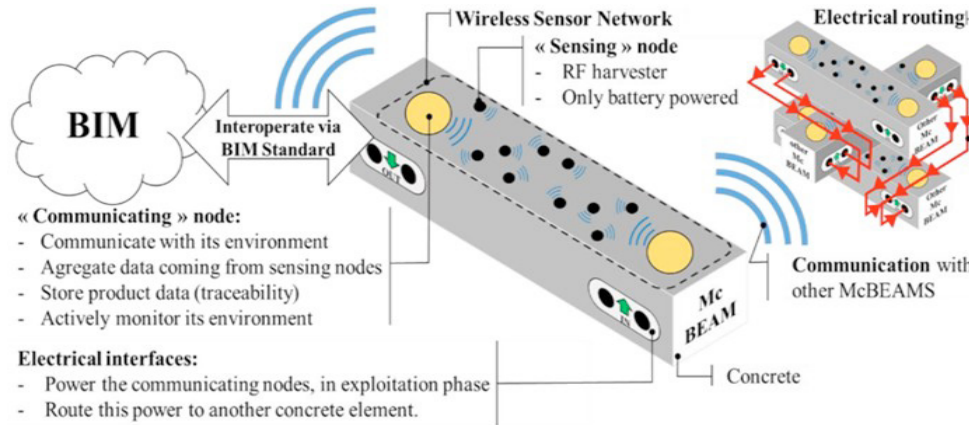


Fig. 1. Description of the McBIM Project

Explainable decision-support with ontologies (LIB): how to use the collected data is a current issue. Not only is this data issued from numerous data sources, but in order to interpret it correctly one must associate it with pertaining context elements such as: type of building element in which the sensor is located, timestamp when the data was collected. Still, coupling these elements with the sensed data is not the issue. One of the objectives of the McBIM project is to explicitly specify, through ontologies, the knowledge of human experts and that is necessary for correctly interpreting the data sensed. Divided into several modules, each about a different domain (e.g. actors, sensors, concrete), the McBIM ontology integrates the data sensed. By means of complex semantic rules, defined on top of the McBIM ontology, the data sensed can be regularly checked regarding a specific expert process or specific compliance requirements. More details about this approach are provided in (Roxin et al., 2022).

A first article written by the whole consortium (Derigent et al., 2019) detailed the different challenges of the McBIM Project. This second article focuses on the different results obtained during the McBIM Project. Indeed, the next section begins with a short description of the McBIM architecture before detailing the results obtained in each of the issues enounced previously.

2. General Architecture of the McBIM Project, based on Holonic Design

The general architecture of the McBIM Project is based on the notion of Holon, first introduced by (Koestler, 1967). This term combines the Greek word *holos*, meaning “whole”,

with the suffix *-on* standing for “part”. A holon consists of a physical part and a digital part. According to the Janus effect (Koestler, 1979), holons can be grouped into a whole to form hierarchical structures called holarchies. The Holonic Paradigm is the fundamental concept of the Holonic Manufacturing Systems (HMS) (Monostori et al., 2003), where products are considered as product holon.

In our work, communicating materials are depicted as material Holons, subtype of product holon, with a physical part consisting of a concrete structure equipped with wireless nodes, linked to dedicated software agents and databases in the digital part, as shown in figure 2. Material Holons can be aggregated into recursive holarchies to form material Holons of higher levels. In the framework of the McBIM project, the WSN of the material holon is made from heterogenous nodes. Indeed, a McBIM WSN is composed of:

- *sensing nodes (SN):* they are battery-free nodes capable to collect data measured by sensors. They are powered via radio-frequency energy harvesting, each one being linked to a dedicated communicating node to which they periodically send data.
- *communicating nodes (CN):* they are nodes with higher computational capabilities, equipped of capable to compose a wireless mesh network with each other, to collect and route the data to a CN serving as a base station. ach CN can have two communication interfaces, a long-range one (i.e LORA) and a short-range one (i.e Zigbee or BLE). CNs can also aggregate data coming from SNs or other CNs.

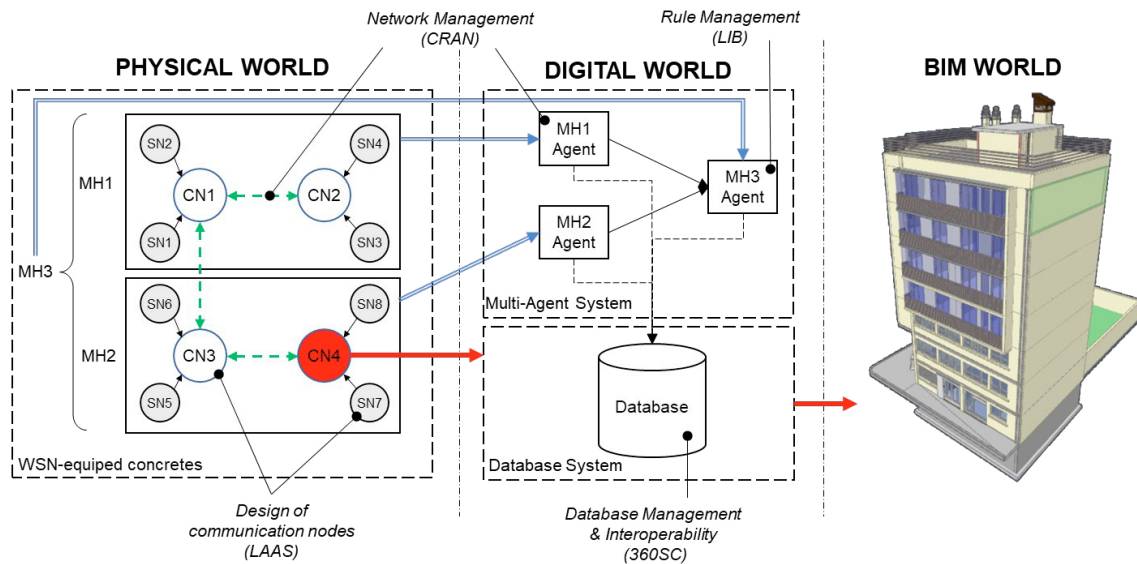


Fig. 2. General architecture of the McBIM Project

Collected data are then sent through the internet to a digital platform, composed of two elements: a multi-agent system and a database. This digital architecture is inspired from the early works of (Wong et al., 2002). Here, the multi-agent system serves as a repository of agents monitoring the physical part they are responsible for. Agents can also be used to integrate the expert knowledge. All the data coming from the different physical parts are gathered into a unique database. In the example of figure 2, they are 3 Material Holons MH1, MH2, MH3. MH1 has a physical part MH1 concrete composed of a concrete structure equipped with a network of 2 communicating nodes (CN1 and CN2) to which 4 sensing nodes are attached (SN1 to SN4). This physical part is linked to an agent MH1 that monitors the physical part MH1 by executing its expert knowledge, if needed, formulated via rules or algorithms. MH1 agent can execute these procedures and may request MH1 data stored in the central database. These data are coming via the network of communicating nodes CN1 to CN4, CN4 being the base station. In this example, MH3 is an aggregation of MH1 and MH2. The physical part of MH3 is then a composition of the network of MH2 and MH3, linked to an agent MH3 of higher hierarchical level. On Fig. 2, the different partner contributions are identified. In the following, the results and perspectives of these contributions are detailed.

3. RESULTS OF THE McBIM PROJECT

3.1 Integrating WPT-powered nodes into the concrete

Several prototypes have been developed to provide a hardware proof-of-concept for the WSN, both for the communicating (CN) and sensing nodes (SN). Because the SN are fully embedded into reinforced concrete (a highly constrained and aggressive environment, especially for the electromagnetic waves) for long-term applications, these must be designed to reliably operate for decades. That is why

these are battery-free, wirelessly and remotely powered and controlled by a wireless power transfer (WPT) system and based on reliable wireless communication technologies. The CN must collect the data sent by the SN and share all these both in the physical and digital worlds and ensure the SN's remote control and power.

In their current version, the CN meet all their requirements both in term of data and power. These are able: 1) to collect all the data sent by the SN for a range of at least 10 m from a reinforced concrete beam (but even higher regarding the chosen wireless communication technology); 2) to locally process and store the collected data; 3) to share and store the data both in the physical world (through a mesh network of CNs) and the digital world (through the Internet), but also locally and remotely with the stakeholders (currently through Wi-Fi, Ethernet, and/or cellular networks); and 4) to wirelessly power and control the periodicity of measurement and transmission of the SN located in their neighbourhood by the use of a WPT system. Thus, the CN are based on two sub-systems: a gateway to operate with the data, and a radiofrequency power source to recharge the SN. The power source generates a 868 MHz continuous wave with a EIRP of +33 dBm (or 2 W) (the maximum power regionally allowed according to (ETSI, 2014)) and is controlled by the gateway (in terms of activation, output power, etc.). A WPT system: 1) allows to ensure the energy autonomy of the battery-free SN located in its neighbourhood, 2) is independent of the deployment environment or of the targeted application (opposite to ambient energy harvesting solutions), and 3) allows in the proposed configuration (radiative electromagnetic waves at 868 MHz) a range of several meters (successfully tested up to 11 m) and a good trade-off between the range of use and the size of the antenna (thus, of the nodes), both correlated to the wavelength.

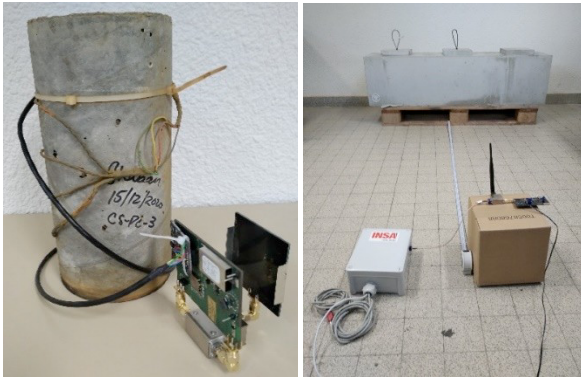


Fig. 3. Left) Prototype of a fully integrated sensing node (size: 8 cm x 6 cm x 5 cm) driving a resistivity sensor; Right) Prototype of a communicating node (LoRaWAN gateway and radiofrequency power source) during an experimentation with 3 sensing nodes embedded in a reinforced concrete beam located at 2 m from the communicating nodes.

In their current version (figure 3. Left), the SN meet all their requirements both in term of data and power. These are able: 1) to collect different kind of parameters from the reinforced concrete (whose the temperature (based on state-of-the-art thermodiodes (de Luca et al., 2015)), the temperature and relative humidity (based on off-the-shelf sensors, and for instance for applying the maturity method), the mechanical deformation (based on strain gauges) and the electric resistivity (based on resistivity sensor, and for instance for estimating the corrosion rate)); 2) to pre-process and wirelessly transmit the collected data to the CN (currently by using LoRaWAN or Bluetooth Low Energy wireless communication technologies (more details are respectively available in (Loubet et al., 2022a) and (Loubet et al., 2022b)), for a range of at least ten meters from a reinforced concrete beam (but even higher for LoRaWAN (kilometers successfully tested in outdoor)); and 3) to be energy autonomous for long-term application by being battery-free and wirelessly powered and controlled by the CN through their radiofrequency power source and their tuning. Only off-the-shelf components have been used for the energy management part.

In this configuration, the range of use of the SN by the CN is limited by the WPT (more because of the regulation and the design choices, than the technologies) and not by the data communication. Tests have been successfully achieved in the air for a distance up to 11 m and from a reinforced concrete beam up to 2 m (Fig. 3. Right) (limited by logistical aspects), but higher ranges are expected. Moreover, it is possible to locate only the sensor and not the full SN into the reinforced concrete to release the electromagnetic constraints and provide a wider range of use. In this way, the constraints in terms of size and shape can be lighten too. The provided range is – at our best knowledge – the highest tested and only (Pizzotti et al., 2017) expects higher ones but by using home-made energy management component. Finally, – at our best knowledge – we provide one of the first fully embedded resistimeter (Corva et al., 2020), and the first fully embedded sensing nodes wirelessly powered and controlled, thus fully energy-autonomous, dedicated to long-term reinforced concrete SHM applications.

3.2 Eco-efficient network management via agents

Sensor networks energy efficiency over a long time is a huge problem. Moreover, deploying such wireless systems in concrete material increases the challenge. An impressive quantity of research articles was produced in the last two decades to extend the lifetime of these kinds of networks. Some hardware solutions were proposed to reduce energy consumption or to harvest environmental energy like the WPT-powered system developed in the previous section. Other works proposed algorithms to optimize the network itself, by optimizing either the communication routing architecture (Wan et al., 2019), or the radio communication usage with duty-cycle techniques or in-network aggregation methods (Wan et al., 2020b). Two major limits arise : 1) in our context, classical energy distance-based consumption models which are commonly used in literature are unexploitable (distance estimation is a very expensive energy activity) and insignificant (because concrete material is a heterogeneous environment), 2) there is no global and optimal solution to optimize and distribute energy consumption across communicating nodes, because classic approaches are fully distributed over the network, and thus provide local and suboptimal solutions.

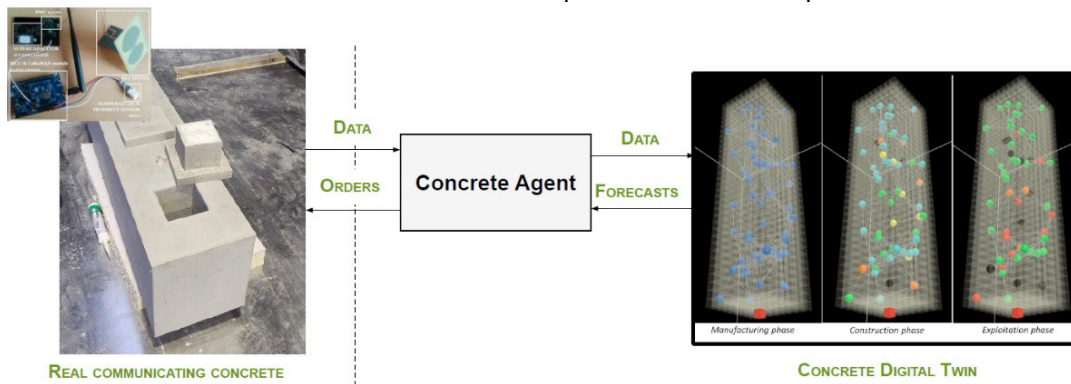


Fig. 4. Energy concrete digital twin

We tried to integrate the most promising literature solutions with a cross-layer view and adapt them to our context (without any significant energy propagation model). In (Wan et al., 2020b), a simple energy-efficient data gathering protocol for linear architecture is proposed. This paper developed energy consumption models to compare two kinds of data collection: without aggregation (no treatment for intermediary nodes) or with aggregation (in network processing). It was experimentally proved that gathering data with aggregation allow homogenizing the consumption all along the communication chain. We developed other energy consumption models to extend the approach to several ways for aggregating data (lossy or lossless aggregation) and to every kind of network architecture (chain, tree, cluster, or hybrid structure). To exploit these models, a recursive multi-agent system is proposed to manage both the individual remaining energy of each wireless node but also the overall consumption of a concrete element. Indeed, energy consumption models are executed by agents grouped into recursive structures; constituting a digital twin of the real communicating concrete (as depicted figure 4). This digital tool allows to represent and simulate the energy consumption of each node in time. This centralized decision system can forecast energy evolution and reconfigure the physical network with an optimal solution if required.

3.3 Data storage and interoperability with BIM applications

These previous works have been (or are in the process to be) integrated to the 360SmartConnect platform, originally dedicated to trace concrete products all over their lifecycle. By integrating laboratory works, the 360SC McBIM platform can manage and collect data from McBim devices, located within structural elements of construction. Sensors and PowerSupply orders are transiting through McBim Broker, via low-power wide-area networks. McBIM Platform CoreSystem stores data from field, characteristics of devices, and make reconciliation with data from 360SmartConnect platform for asset and operation traceability. To complete McBIM services, specific interfaces are available: a dedicated one to manage devices and their power management, a grafana-like interface to visualize collected data, past or real time, and another interface to simplify expert rules management through a BIM ontology. A global system of McBim webservices finally permits to any BIM Software to benefit of these located and enriched data coming from the field (figure 5).

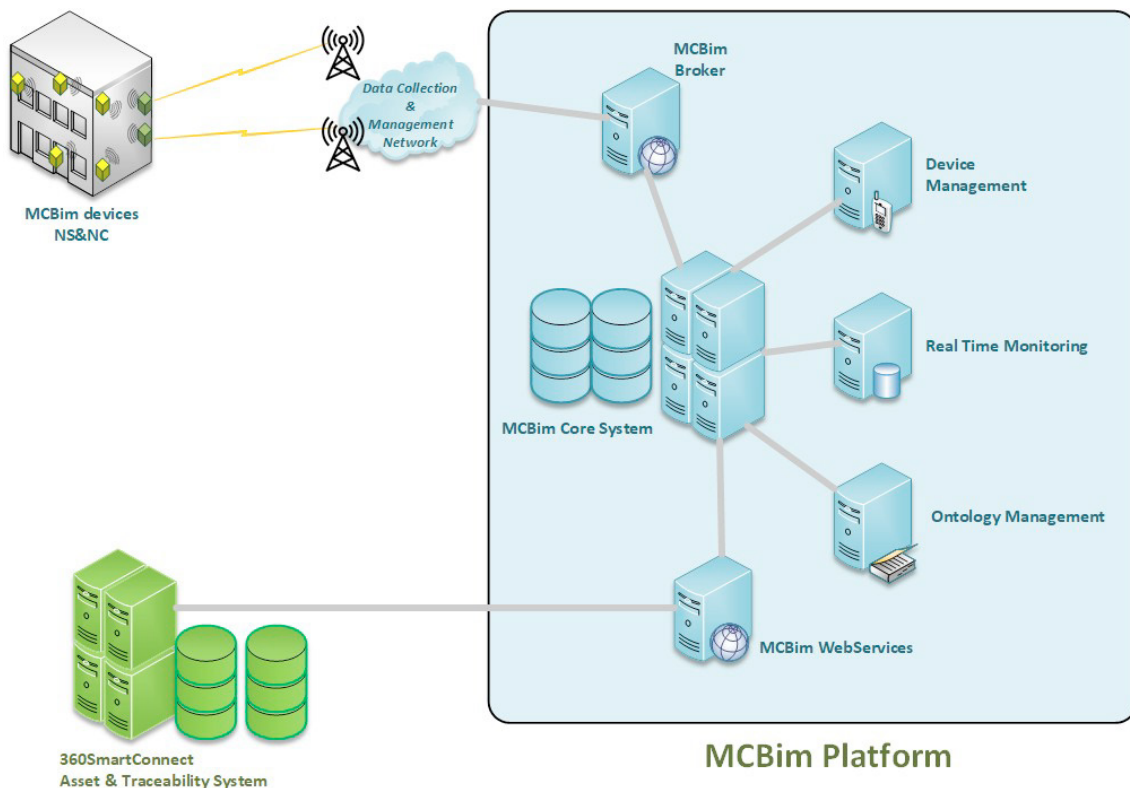


Fig. 5. McBIM Platform structure

4. CONCLUSIONS

This paper is an overview of all the works gravitating around the McBIM project, which worked on parallel but intricate research and technological issues. The use of the holoic paradigm gave a way to integrate the physical and digital world, via the connection between WSN and agents linked to databases. Laboratory results are very promising. They now must be confirmed by future on-site applications.

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