Wireless monitoring of historic structures using sensor networks – an overview about several recent implementations

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Abstract

Structural health monitoring of historic structures using autonomous wireless sensor nodes becomes more and more important for conservators and restorers. In regard to the monitoring devices and data processing techniques several boundary conditions are special for the field of cultural heritage compared to other (wired or wireless) applications. These boundary conditions are summarized and several case studies are presented including indoor and outdoor measurements. Since a single monitoring technique among the actually existing might not cover all requirements this overview paper illuminates a selection of four different European monitoring systems along with demonstrations of their performance at field applications.

Keywords: Wireless sensor networks, structural health monitoring, cultural heritage, historic structures

1. Introduction

The preservation of historic structures for next generations is one of the main tasks, conservators are responsible for. In order to preserve historic structures and make them available for private and public use, it is more and more required to understand the deterioration processes mainly caused by their local and global environment. Historic structures and objects of the cultural heritage are in itself complex assemblies requiring an integrated investigation approach, with contribution from many disciplines. When in addition to present health state of the object, the interest includes a prognosis of its development, numerous parameters have to be kept into account and the landscape becomes very complicated because different types of damage can affect the life expectance of the structure. Therefore it is required that investigations are complete and reliable for the damage and its evolution to be detected. This requires novel techniques like monitoring methods based on wireless sensor devices that can be operated autonomously i. e. with extensive maintenance and efforts in terms of costs and personal.

2. Advantages of wireless systems

The recent developments in micro-electronics, micro-sensing and wireless data transmission are in particular useful for applications in the field of cultural heritage because of several reasons. Among others are the following aspects:

- minimally invasive mounting
- miniaturisation and minimal installation (aesthetically appealing)
- interchangeability, flexibility
- platform for different sensors
- integrated data analysis
- cost-efficient

2.1 Minimally invasive mounting

The ideal sensor in this environment would be one that does not affect the object under observation at all. Sensors need to be used that do not interfere with the object due to coupling to a surface or similar issues. Drilling holes or fastening devices is often not allowed. If this is inevitable (e.g. measuring the temperature or moisture inside a material like stone) the deterioration should be minimal.

2.2 Miniaturisation and minimal installation

Most structural health monitoring (SHM) systems require cabling, which is not aesthetically appealing. If cables cannot be hidden their presence can certainly disturb the visual impression of a monument and wireless sensing systems are first choice. Besides this, since SHM uses often boxed sensors (“sensor nodes” or “motes”) of a certain size, smaller components are required and micro-sensing is preferred.

2.3 Interchangeability and flexibility

Because of the uniqueness and complexity of historic objects and structures a measuring system has to be very flexible, both in regard to the attached sensing parameters (see next section) and to the deployment. Very often damages have several reasons (humidity, salt, harmful gases etc.). In addition different types of deterioration can occur. Both cases require the use of different sensor types and a deployment at various positions. Wireless systems are doing a good job in this case since rearrangement of sensor nodes is usually easy and not laborious.

2.4 Platform for different sensors

Sensors are required for the measurement of structural and material values e. g. temperature, humidity, gases, crack opening, air velocity, surface deterioration, chemical attack, ambient light, deformation, displacement, inclination or vibration. Using sensor platforms as described in the following any kind of low power sensor can be used in combination with the platform. A typical platform or sensor node allows for a combination of two or even more sensors being attached to a single node.

2.5 Integrated data analysis

Acquiring monitoring data with different sensors is not sufficient if it is not clear how to handle these data. Their analysis and interpretation is a difficult task due to the high complexity of the deterioration processes involved with indoor and outdoor environment. Most of the models that are currently used either do not consider complex data from the changing environment or are based on assumptions that are rather precise or on the contrary they are too complex to be implemented for continuous in-site monitoring evaluation. This is true, because they are based on calculation methods which require stand-alone software or needing expert knowledge for execution. Consequently, in modern wireless sensing systems also models of the deterioration processes have to be implemented into the node allowing for alarm triggering and making monitoring more efficient. Sometimes this type of SHM systems are called “smart”.

2.6 Cost-efficiency

Structural health monitoring (SHM) systems attached to historic structures as well as to sculptures, statues or artefacts in museums or at other places have to be cost-efficient, especially, if they are considered of lower importance due to their smaller dimension, lower fame or reduced preservation budget. This is possible through the reduction of wiring costs typical for WSNs and the implementation of data processing in the nodes that reduces the time and effort of a conservator. Novel approaches would deliver a “place-and-forget” SHM solution. Moreover are wireless sensor platforms optimized for the implementation of small micro-sensors like micro-electro-mechanical systems (MEMS). Most (if not all) sensors for physical or chemical properties are today implemented in MEMS. This is in particular true for the structural and material values described in section 2.4. Besides cost-efficiency, MEMS enable for low power sensing and miniaturisation (section 2.2) and can easily be combined with a micro-processing unit (digital signal processor, DSP) for an integrated data analysis (section 2.5) or with miniature video cameras.

3. Case studies and monitoring techniques

One can probably learn best about the applicability of wireless monitoring systems from existing deployments. There are several of such systems around and they all offer different solutions using different hardware and post-processing techniques. Some of them are focussing on applications in the field of cultural heritage, but most can be implemented also in other environments e. g. civil engineering structures like bridges or building.

In the following, a selection of different monitoring concepts is described – all of them are reviewed in regard to SHM of historic structures and all are commercially available. The selection of devices and methods is somehow artificial and certainly not comprehensive. More information can be found in the literature (e.g. in [1]).

Fig. 1. Smartmote^{WS} sensor node [2]

3.1 Smartmote^{WS}

The wireless devices of the Smartmote company in Germany focus on wireless sensor network techniques, where networks of several or many sensor nodes are used to monitor a structure and the data are send to a sink after pre-processing in the mote. The Smartmote^{WS} wireless sensor node (Fig. 1) is equipped with a microcontroller MSP430 F1611 featuring 10 kB of RAM and 48 kB of program memory (flash). It comes with a 16-bit RISC processor offering several power-down modes with low sleep-current consumption. This permits the sensor node to run for a long time period. A wireless transceiver following the ZigBee standard (Chipcon CC2420) is used; the theoretically achievable maximum data throughput rate of the system is 250 kbps. Due to its modular concept the one or two lithium-thionyl chloride primary batteries (Li-$SOCl_2$) can be supplemented by high energy super-capacitors or a solar panel attached to the sensor node casing.

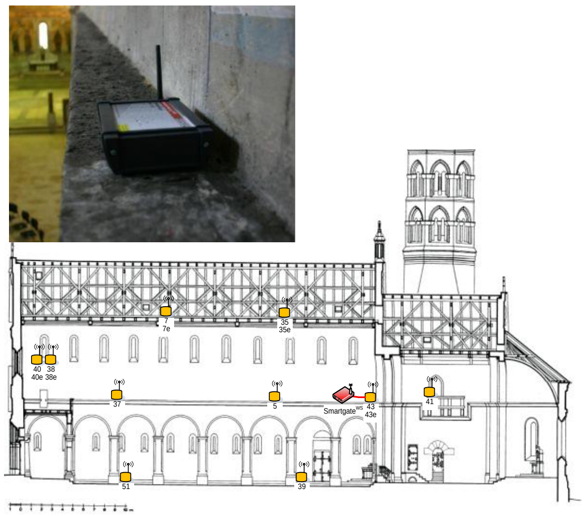

Fig. 2. Sensor node distribution and (inset) single node on a ceiling inside the Johanniskirche, Schwäbisch Gmünd, Germany [5]

The multi-sensor board supports many types of sensors including MEMS, strain gauges, temperature and humidity sensors (e. g. Sensirion's SHT15) as well as conventional accelerometers. The sensor nodes are communicating to a base station (sink) called Smartgate^{WS} that can theoretically be away up to several hundred meters (line of sight). In this case a distance of more than 40 m was crossed between sensor node and gateway. A Smartgate^{WS} is a small industrial Linux-PC with a GPRS/UMTS-modem. All data collected from the wireless sensor network is transmitted through the internet and stored in a SQL-database. From that database further data analysis is conducted.

Main functionality of this sensor node was developed during the project "Smart Monitoring of Historic Structures" (SMooHS) [3, 4] sponsored by the European Commission in the 7th Framework Programme. In the meantime it is used and further developed during several SMooHS field applications that are for example located at the Holy-Cross Minster, Schwäbisch Gmünd (Germany), Schönbrunn castle, Vienna (Austria) and the Bode Museum, Museums Island, Berlin (Germany). Most of the data can online be visualized at the Smartmote webpage [2] together with the deployment of the individual nodes.

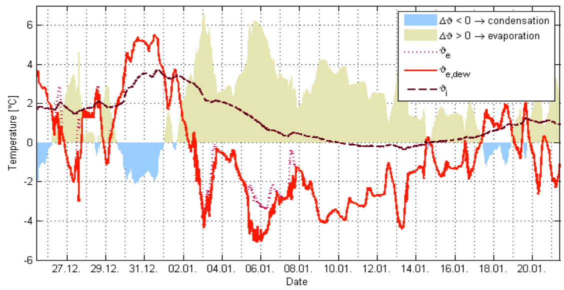

Fig. 3. Temperature measurement and dew-point calculation [5]

Two other applications also in Schwäbisch Gmünd are the St. Salvator chapel and the Johanniskirche (St. John's Church). Since 2009, indoor and outdoor climate data has been collected at various locations of the Johanniskirche (Fig. 2). The goal is to observe the micro-climate (e. g. the moisture in the structure) preventing future damage to both the structure and interior decoration due to resulting condensation [5]. As an example Fig. 3 shows a set of temperature data (1 month) from one indoor node. The dew point temperature is compared with indoor temperatures averaging values every 15 minutes and displayed at a webpage. In real time a decision is made if doors or windows need to be open or closed. During the measurement campaign a rehabilitation of structural components to minimize condensation in future was performed and the deployment is still used to confirm the success of these activities.

3.2 Smartbrick®

The Smartbrick® platform [6] has been developed especially addressing low sensor count applications and is different from the sensor network principle. The platform (Fig. 4) embeds a large set of self-referenced sensors, features a multi-year battery lifetime and communicates using the GSM/GPRS mobile phone network. In addition to typical features of common wireless sensor platforms, the Smartbrick® device is equipped with a trigger system intended to detect acceleration peaks as low as 18 mg in the typical frequency range of structural vibrations induced by random environmental excitation or small seismic events. Having a power consumption of less than 66 μW, the trigger system can be kept continuously armed even when the device is kept in deep-sleep mode, with negligible effect on the battery life. The trigger can wake up the device within 150 ms in order to acquire dynamic events from up to eight independent channels, with a total maximum sampling rate of 4100 S/s and memory depth of 64 k samples.

Fig. 4. "Smartbrick®" wireless autonomous SHM platform [6]

Sensors embedded in the device typically include environmental and substrate temperature, high-stability inclinometers on both pitch and roll axes and a tri-axial acceleration sensor. Pre-conditioned inputs for additional specific sensors are provided as well, such as direct inputs for strain gauges, crack and displacement gauges, load cells, relative humidity, wind and rainfall sensors as well as Laser displacement gauges.

Fig. 5. Installation of Smartbrick® platform at the "David" statue in Florence [7]

Smartbrick® has been used to monitor the stability of the basement and the environmental vibration events of statues in museum environments. One installation was at the statue "David" of Michelangelo at the Galleria dell'Accademia in Florence (Italy) (Fig. 5). In addition to the basement inclination and temperature data, seismic trigger capability is used to capture sporadic dynamic events. These data are compared to data from a Bragg-type fibre-optical sensor system (FBG) installed on the artwork to monitor the evolution of cracks.

As an example for data analysis Fig. 6 shows strain measured by an FBG, compared with the temperature for a ten day period. Crack opening variations are opposite to the temperature variations, since an increase in temperature causes an expansion of the marble in the vicinity of the crack itself, resulting in a decrease of crack opening.

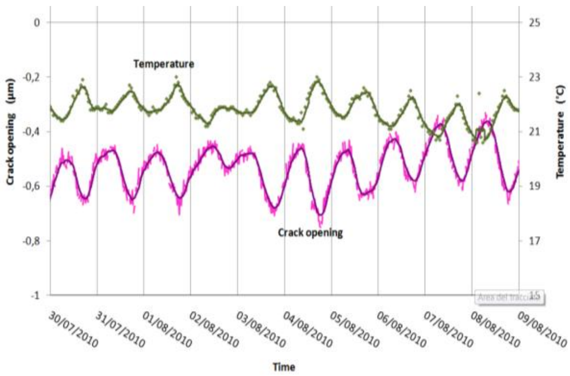

Fig. 6. Comparison of crack opening and ambient temperature [6]

Some other field application of the *Smartbrick®* platform are at the Palazzo Malvezzi, a historic building in Bologna (Italy), the Bode Museum, Museums Island in Berlin (Germany), the Palazzo Camponeschi in L'Aquila (Italy) that was severely damaged by the earthquake of 2009 and the Khrasha-Zahda building, a typical example of Turkish-style historic heritage located in the old town of Hebron (Palestine).

3.3 CulturBee

During the CulturBee project a network-based system for remote and wireless monitoring and control of historical and cultural buildings like churches and museums was developed by researchers of the Linköping University in Sweden [8]. The wireless sensor networks can be used for remote monitoring of temperature and relative humidity and for remote climate control at various locations, both indoor and outdoor, of historical objects. Other types of sensors for light, CO_2, fire, and radiation can also be added to the CultureBee system. Since it is fully wireless it can be placed in a harsh environment, or it can even be used during transportation of goods in cars, trucks or trains. The expected battery lifetime of a CultureBee sensor module is ten years with a sampling interval of every fifteen minutes for data acquisition.

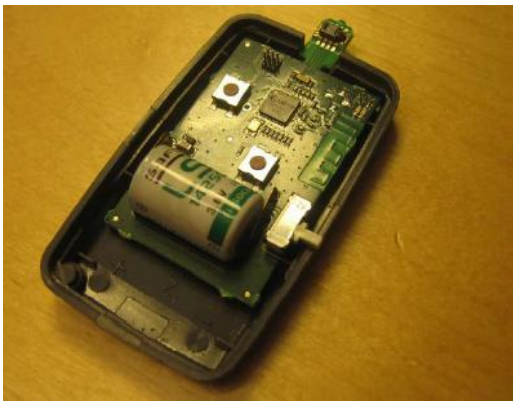

Fig. 7. CulturBee sensor node [7]

Two different types of sensor nodes where developed. The first (Fig. 7) is a so-called *ZigBee sensor module*, which can sense the temperature and relative humidity data and act as an end device in a network. The second module is a *ZigBee radio* with external power amplifier and low noise amplifier. With extra adapter boards, the module can be used to act as a router or a coordinator. Furthermore, the module can also be used to connect to other types of sensor and act as an end device. The used CC2430 RF transceiver includes an industrial-standard 8051 microcontroller unit for signal processing.

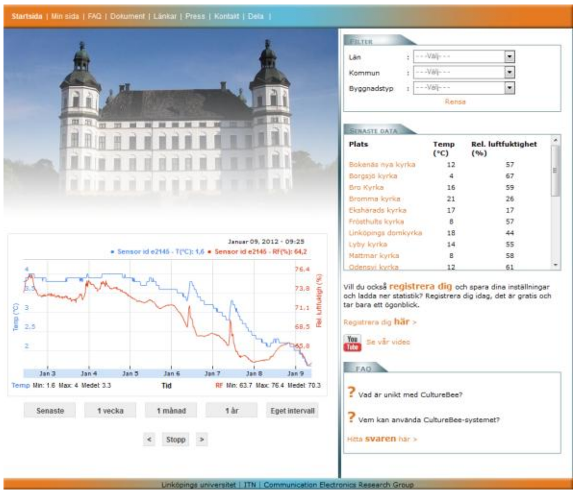

Fig. 8. Screenshot of the CulturBee webpage [8], where data from up to 26 locations each equipped with several sensor nodes can be displayed

The local wireless sensor network is programmed to such that the coordinator will form a local network as soon the power is switched on. All the other devices will automatically join the network when power is turned on and a network is found. The wireless sensor network is further connected to a remote main server via the internet through a GPRS/3G/Ethernet connection for central storage, monitoring and maintenance.

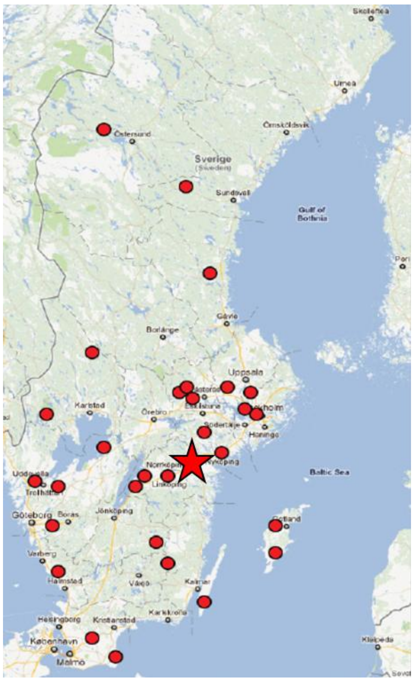

Fig. 9. Location of the 26 monitoring sites of the CulturBee project [9]

A control function can be added to the sensor network to control radiators and ventilation systems, based on the sensed data from the wireless sensor network – similar to what was described for the Smartmote project at the Johanniskirche (section 3.1). There are several ongoing field measurements of the CultureBee project in Sweden, e. g. at the Skokloster Castle in the province Uppsala (Fig. 8), at Linköping Cathedral in the Östergötland province and at up to 24 more locations that can be displayed via a webpage (Fig. 9) [8].

Fig. 10. Essebi monitoring node at the Cathedral of L'Aquila, built in the 13th century [10]

3.4 Essebi monitoring system

The structural health monitoring system of the Essebi company in Italy [10] includes several bi-directional 4-channel 16-bit NI WSN-3202 analogue nodes (Fig. 10). Data transmission of the nodes to the gateway is following the IEEE 802.15.4 standard (Wireless Personal Area Networks, WPAN). Different sensors can be connected to a node, like direct linear slide potentiometers for crack monitoring and distance measurements between masonry walls (linearity = 0.2 % of the sampling rate ± 25 mm), inclinometers for masonry walls and historic columns (linearity = 0.5 % of the sampling rate ± 0.5°) and pressure cells for measurements at the bottom of columns (linearity = 0.25 % of the sampling rate of 40 bar). The fourth channel is reserved for temperature measurements. A WSN gateway collects data from distributed nodes and is connected via Ethernet to a PC that users can remotely access via a GSM modem. Alternatively, one can use a WSN gateway that is basically a cRIO controller using a 533 MHz processor coming with 2 GB onboard storage. Using a standard (wired) cRIO device as a gateway enables for the use of an optical sensor interrogator module to connect Fibre Bragg Grating (FBG) sensors.

Fig. 11. Cathedral of L'Aquila and installation of sensor nodes via a basket hanging from a crane

One of the actual field monitoring structures is the Cathedral of L'Aquila, built in the 13th century (Fig. 11) [11]. The church has suffered from numerous disasters throughout the centuries, which were regularly followed by restorations. The neoclassical façade is characterized by two massive bell towers on each side. The interior consists of a nave that was partly damaged due to the collapsed cupola of the main altar during the April 2009 earthquake (magnitude M_W = 6.3). This disastrous event only spared stumps of the pillars supporting the cupola, portions of the perimeter masonry walls, and some parts of the ogive apsis. The task was to monitor portions of the cathedral that are structurally isolated from each other because of the collapse. Most parts are outdoors because of the complete lack of coverage from the end of the nave to the apsis. The modular solution based on groups of sensors allowed for the measurement of different physical variables (Fig. 12). The connection of the sensors to WSN nodes that are linked to a centralized gateway minimized the use of cables that could be damaged during the restoration, what might disrupt construction activities.

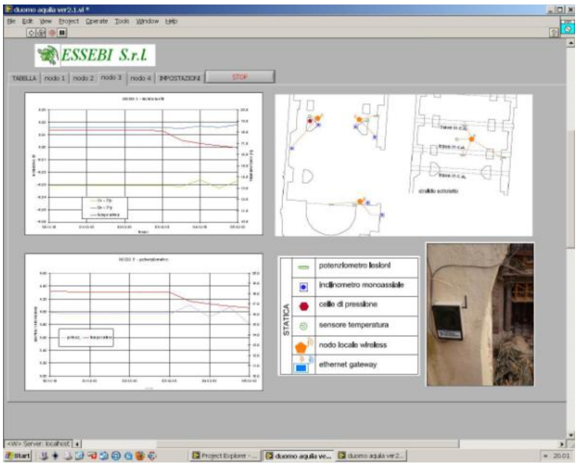

Fig. 12. Screenshot of the monitoring software of Essebi company [11]

Currently, the connection is point to point (*star topology*) and uses a GSM phone call to log in. It is planned to add an internet connection interface to the system for continuous remote management done by the central "Civil Protection's Project Direction" that is responsible for all activities in the L'Aquila area. The ability to activate alert thresholds to trigger events of interest will be implemented.

4. Conclusions and outlook

Wireless sensor methods can successfully be used to monitor objects and structures of our cultural heritage. In many (but not all) cases they are first choice due to cordless deployments and their easy and flexible installation. Since there are so many valuable historic objects and the budget to conserve them is limited, cost-efficient techniques are required as well as data processing techniques reducing the maintenance costs and visual inspections to a minimum.

Up to now developments of wireless sensor nodes and networks was a deal of research groups and smaller companies. Larger companies and manufacturers of measurement equipment are getting more and more aware of this market. However, a unique solution that is able to fulfil all requirements of SHM applications in the field of cultural heritage is not at hand. This is in particular true for pre-processing hard- and software solutions including a large variety of chemical and physical sensors as well as the combination with user-defined arbitrary models and alarm settings/triggers. Since there is a large variety of materials and material compositions as well as different deterioration scenarios depending on indoor and outdoor conditions and many other circumstances a "Swiss Army Knife" for these types of applications is not in sight for the near future.

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