Long-Term Wireless Monitoring of Historic Structures – Lessons Learned from Practical Applications

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ABSTRACT

Monitoring of historic structures is quite a challenge. Ideally any installations have to be non-destructive and invisible for which the application of wireless monitoring systems seem to be a good solution. The situation becomes challenging if the desired monitoring focuses on acquiring and analyzing data like stress, strain, inclination, salt and moisture content inside materials that require reliable sensor technologies and adequate signal conditioning. The main challenges in this context are the power supply and reliability over longer monitoring periods. To remain cost-effective and practicable, a balance between the monitoring task adequate to the expected result from the monitoring and the time and effort to perform the monitoring must be found. This is why wireless monitoring systems frequently have to be customized. The paper discusses research results of the European project SMooHS and developments made with respect to monitor historic structures with wireless sensor systems. The focus is on wireless monitoring solutions that have found to be appropriate for long-term monitoring (periods larger 1 year) of historic structures.

INTRODUCTION

Europe has a wealth of historic structures due to its ancient roots and love of fine architecture throughout the ages. It is vital that these structures are preserved if possible because they represent a major part of cultural heritage. Each country has its own interpretation of the various architectural styles, which makes every structure unique and of great value. As noted by Blaise et al. [1], "heritage sites match the interests of many in that they materialize historical influences and differences".

Of particular importance to structural engineers and heritage conservators alike is the development of a Wireless Sensor Network (WSN) tailored for the stringent

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requirements of historic structures that will increase knowledge about older material properties and building. This can help not only with the analysis of the physical structural integrity, but also moisture migration in the walls, which can damage wall decoration and plaster, and in extreme cases, lead to structural instability. An effective and reliable WSN for these applications will aid in quick assessment of the current condition of a structure by analysing recent to real-time data as opposed to relying solely on experienced-based estimations. In terms of key goals to advance the use of WSNs, Swartz et al. [2] identified the following criteria: controlling cost, reducing energy consumption, ensuring reliable communication, and scalability.

WIRELESS MONITORING SYSTEM PRINCIPLES AND SYSTEMS

Wire-based measurement systems for SHM consist of several sensors applied to the structure at relevant locations. Sensors are available for a plethora of physical quantities, and have to be chosen according to the application demands. The sensor readings are analog-digital converted in a central unit, where the digital data is also stored. Many systems allow online-retrieval of recorded data. In contrast to these aforementioned systems, wireless systems have a decentralized data acquisition. There are many different wireless sensors that have been developed by researchers all over the world to be used for SHM. A comprehensive review of available wireless sensing units is given by Lynch and Loh [4] that show the cutting edge at that time. Many of those sensing units are just prototypes followed by further developments. However, a lot of shortcomings especially with respect to reliability and practicability are still obvious. One problem is still the conflict between power consumption and system bandwidth. Much research is going on in the field of energy harvesting methods to avoid use of batteries. However, in practice there will always be a situation where you need to operate a wireless node by batteries only. Thus, energy harvesting is just an option. The system bandwidth is mainly restricted by the wireless communication throughput that is limited. That is why multihop network algorithms, mote clustering and in-mote data processing and reduction are considered in the recent research [4], [5], [6]. Although numerous commercialized smart sensors are also available together with some application software from different companies, most of these sensor networks are in a basic configuration just wireless data acquisition systems that only transmit measured raw data to a central base station for further processing. Moreover, most of the systems do not fulfill the requirements with respect to robustness, long-term stability, long-term battery operation or sensor reliability.

WIRELESS MONITORING SOLUTIONS DEVELOPED IN THE SMOOHS PROJECT

The purpose of the research conducted within the SMooHS-project was to develop cost-effective and reliable wireless sensor technologies appropriate for structural health monitoring and real-time data analysis. Two different kinds of systems were further developed within the SMooHS-project (see **Figure 1**) that use relatively simple wireless communication for several reasons discussed later on.

The self-contained wireless sensor called “Smartbrick” (see **Figure 2**, left) represents a simple and quick to install solution, where the wireless sensor acquires relevant data, eventually analyses it and then sends it by wide area mobile connection directly to the user or a central server for further analysis. 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, LASER displacement gauges, etc. In addition to typical features of common WSN platforms, the "Smartbrick" device is equipped with a trigger system intended to detect acceleration peaks in the typical frequency range of structural vibrations induced by random environmental excitation or even small seismic events. Having very low power consumption, the trigger system can be kept continuously armed over very long periods. The trigger can wake up the "Smartbrick" device in order to acquire dynamic events, thus allowing the performance of additional monitoring tasks such as evaluation of environmental vibrations, providing fast reaction capability to seismic events.

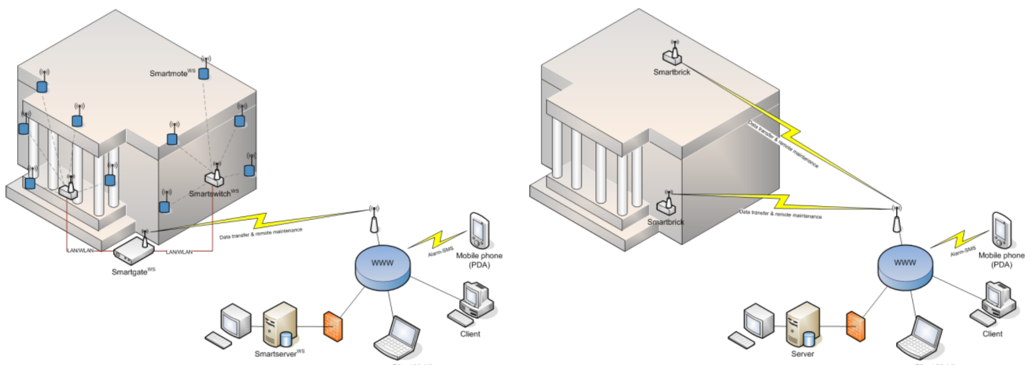

Figure 1. General system layout of wireless monitoring systems: Wireless sensor network (left) and self-contained wireless sensors (right).

The other system developed is a wireless sensor network (WSN) called "Smartmote^{WS}", which is composed of several independent wireless nodes (see **Figure 2**, right), linked to each other by a short range radio communication link, hence building a wireless sensor network. Additional elements of the system are the gateway, which relays the measurement data to a long-distance network for remote access, and a database to save data for later retrieval and optional post-processing. The hardware is optimized to work under harsh environmental conditions as they occur in case of structural health monitoring. Different kinds of sensors could be attached to the wireless mote simultaneously that is various MEMS (Microelectromechanical systems) sensors with digital output, e.g. for the acquisition of acceleration, temperature, humidity, inclination, solar radiation etc. Additionally analog sensors like resistive strain gauges or piezo-based vibration sensors are connectable by using especially developed electric circuits for the signal conditioning. This modular concept allows for customization and optimization for specific monitoring objectives. Currently, several additional sensor boards are available: a signal conditioning board for interfacing piezo- and PVDF- sensors for acoustic emission and dynamic analysis, a multi-sensor signal conditioning board for strain gauges, displacement transducers and pressure cells in combination with temperature/humidity and vibration measurements, sensor boards for high precision inclination measurements, for high-impedance potential measurements as well as for high-impedance resistivity measurements in the field of electrochemical analysis [7]. As battery life is one of the primary limiting factors the node is designed with this in mind. One scenario that shows the long-term operation capability is by acquiring and sending temperature and humidity data with a data-transmission interval of five minutes. Taking into account the duty cycle, the average power consumption is estimated to be 30 µA in worst case. Extrapolating from this measurement, the used 7.7 Ah Lithium Thionyl Chloride Battery could last decades. Although this amount may seem excessive, it was deemed appropriate to provide a large factor of safety so that several other sensors can be attached to the wireless nodes, some of which will consume much more energy.

Both the self-contained wireless sensor and the WSN are operated remotely from an operation and maintenance terminal. While the self-contained wireless sensor is ideal for monitoring in a confined area, the WSN is the more competitive solution if data has to be monitored at various locations or rooms.

Figure 2. The "Smartbrick" WASHM platform installed on a structure (left) and wireless sensor node "Smartmote^{WS}" to build up a wireless senor network on a structure (right).

STEPS TO A PRACTICAL APPLICATION OF WIRELESS MONITORING SYSTEMS

As described above, the systems developed within the SMooHS project are not the most sophistic ones if compared to other actual research activities. The reasons for that are described in more detail in the following.

Definition of monitoring tasks

The definition of the monitoring objective at a specific structure is the first aspect an engineer or a restorer has to deal with. Depending on the aspects that might need information from continuous monitoring different information should be collected before the monitoring system is designed and assembled. E.g., if structural problems are of interest basic information might be the results from structural calculations, structural dimensions, material properties, definition of weak points etc. Also duration of the monitoring is of utter importance. Starting from such elemental information the monitoring concept should include information on type of value to be measured, accuracy, sensitivity and robustness of needed sensors, environmental conditions and other exposures that might either influence the structure or material itself or, which is as much important, might affect the reliability of the sensors and of the used measurement technologies, fixing and installation possibilities.

One example of problematic environmental conditions is the measurement of strain of materials like concrete, stone or wood. While the measurement of strain could be made seemingly easy by just attaching a strain gauge to the surface, the actual total value of strain of such materials is a time-dependent function mainly driven by temperature, moisture content and applied stress. Beneath that also the resistance of a strain gauge as well as the data acquisition unit is affected by temperature so that the precise determination of absolute strain has to imply a lot of different possible sources of error. Hence, the determination of absolute strain in changing environmental conditions requires the simultaneous acquisition and compensation of temperature and humidity, which makes it rather complex.

Accessibility of the structure with respect to sensor mounting is also an important site specific factor that must be defined before an appropriate monitoring system could be chosen. If any fixing has to be avoided and even touching is not allowed one has to consider alternatives. One possibility is to use dummy probes and locate it inside the area of interest. Other methods include the usage of contactless sensing principles or installation of the sensors at hidden or less important locations.

Finally, background information about any models that might be useful to analyse the data from the monitoring should be collected to avoid missing measurands and data during the monitoring but also to keep the amount of data that has to be collected as small as needed.

Consideration of cost effectiveness

If the monitoring objective is just simple as an acquisition of air temperature and humidity, there are still some competitive commercial systems (also in form of data loggers) available that are applicable quite easily without detailed knowledge. However, such simple “environmental” monitoring tasks do not effectively meet the terminology of structural monitoring. Complex monitoring objectives require a high degree of customisation especially with respect suitable sensors as well as further hard- and software. A crucial part of the further decision process is to consider costs, which could be distinguished in hardware costs, system integration costs, installation costs, and yearly operating costs (maintenance).

For most applications the initial hardware and here especially the sensor costs play a major role with respect to the total costs, so care should be taken in choosing adequate hardware components and sensors. System integration costs, installation costs and the yearly operating costs are the smaller part of the total costs and do not depend so much on the chosen hardware. However, costs are strongly influenced on the amount of sensors to be installed and their location. If sensors have to be installed only at a few locations inside a structure self-contained solutions like the Smartbrick is most economic. If sensors have to be installed at several (appr. five) locations wireless sensor networks like the Smartmote system become more efficient [9].

Monitoring system design and assembly

System design and assembly could be broken down into three main steps that is the data acquisition concept, the data analysis and distributed computing concept, and the hardware selection. The determination of principles of data acquisition and handling is the first step of the system design, while principles of data evaluation and interpretation are included in the data analysis and distributed computing concept.

This differentiation is made due to the fact that for the second step the desired monitoring objectives come to the fore, which is mainly analysis of the data by adequate and individual methods to be implemented into the software, respectively the application software for achieving the monitoring objectives. The data acquisition concept is more generic, because it defines requirements for choosing the most sufficient hard- and software with respect to monitoring technology limitations.

One aspect one has to deal with is data loss and data corruptness. The data loss rate varies from system setup to system setup and is also strongly influenced by the environment. Some data loss might be acceptable for some applications, but if an important event has to be transmitted that was defined to be critical (e.g. alarm generation in case of structural failure), undefined packet loss rate is unacceptable, especially with respect to a proposed safety index. This means that the effect of data loss must be considered in the monitoring task. It is noticed from several applications that sometimes data loss could be 100% for periods of several minutes up to hours or days and on the other hand data loss rate could be almost zero for another period at the same system without having made any changes.

In many publications wireless monitoring systems and monitoring results are presented that do not reflect the system reliability. However, system reliability is one of the key features for the determination of usability of wireless monitoring systems from the practitioner's point of view. Reliability could be determined e.g. with respect to hardware, sensors, software, environmental conditions etc. It could be assumed that all the hard- and software components are designed to fulfill predetermined requirements. The improvement of the hardware is costly for which reason its optimization during a monitoring campaign is not favorable. This means that the hardware should be well designed and validated. It is more or less the software and the way of data handling that provides an opportunity for further optimization.

In addition to these fundamental aspects, wireless monitoring should be more than just acquiring diverse measurands at different locations of a structure and then storing it in a database. If the monitoring task and the expected result are well-considered, immediate data processing of the data is recommended to avoid collecting large amounts of senseless data no one will look at afterwards. Therefore, distributed computing strategies, which include data acquisition, data analysis and data reduction are of utter importance.

With respect to the restrictions of a sensor node event based data acquisition may become of interest or rather becomes an obligatory task if a critical short event occurs during the time the monitoring system is in sleep mode, thus not capable to recognize this event. Event based monitoring is useful if temporary loads or other influences stress the structure, e.g. trains, trucks, wind, snow or rain, earthquakes or structural failure itself. That means that an object specific event triggers the measurement progress. A case study on which event based monitoring was successfully tested was the detection of human activity (people stepping on the balcony of Palazzo Malvezzi, Bologna). For that purpose the Smartbrick devices have been used to monitor settlement and the possible evolution of seismic-induced damage (see Figure 3). The device is enabled for dynamic data frame capture driven by the seismic trigger system. Figure 3 illustrates a typical time history of a vibration event induced by human activity that has been recorded.

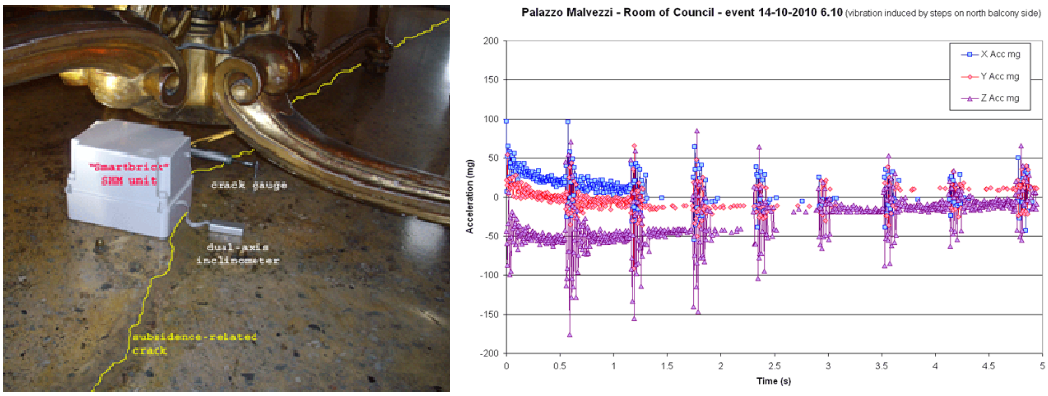

Figure 3. Installation of the Smartbrick device in Palazzo Malvezzi and example of time history acquired during a dynamic event.

Wireless monitoring systems in operation

While the installation of a monitoring system is not as complicated the initial operation of the monitoring system is to be made with care. Sensors must be attached correctly, must be configured and tested or even calibrated to avoid unrecognized malfunction. With respect to the desired distributed computing strategy, also reference data acquisition in combination with a data reliability check and model adjustment is crucial. Based on reference data and the implemented data analysis models, alarm levels or other thresholds should be defined so that user notification or interaction is supported. This is also essential for the detection of potential malfunction of the monitoring system (e.g. sensor or mote failure, discharged battery etc.) and the need of permanent self-monitoring. Although wireless monitoring is expected to operate autonomously for most of the time, system maintenance and user interaction is still needed. This is also true due the fact that the overall analysis and interpretation of the monitored data always require expert knowledge and further decision making.

For convenience in particular with respect to make changes and adjustments in the application software running on the motes system maintenance should be assisted by remote control. This is mainly revision of object specific settings, e.g. model updating, data analysis algorithm updating, modification of alarm levels etc.

Intelligent wireless monitoring and further analysis and interpretation

As it is discussed above, immediate data processing of the data is recommended to avoid collecting large amounts of senseless data no one will look at afterwards. If such immediate data processing is considered, wireless monitoring becomes intelligent and of direct practical uses. Auto-regressive models could be used to identify interrelationship of different physical values in time series and to predict future behaviour. They are well suited for identifying influences e.g. from seasonal weather conditions, repeated loading or other phenomena that occur periodically. Auto-regressive models are used by many researchers to fit measured time series data to stationary data that define an initial status, but at the same time not knowing which changes might occur in future. During further monitoring this data is used in terms of detecting significant changes and characterizing these changes with respect to the monitoring objectives.

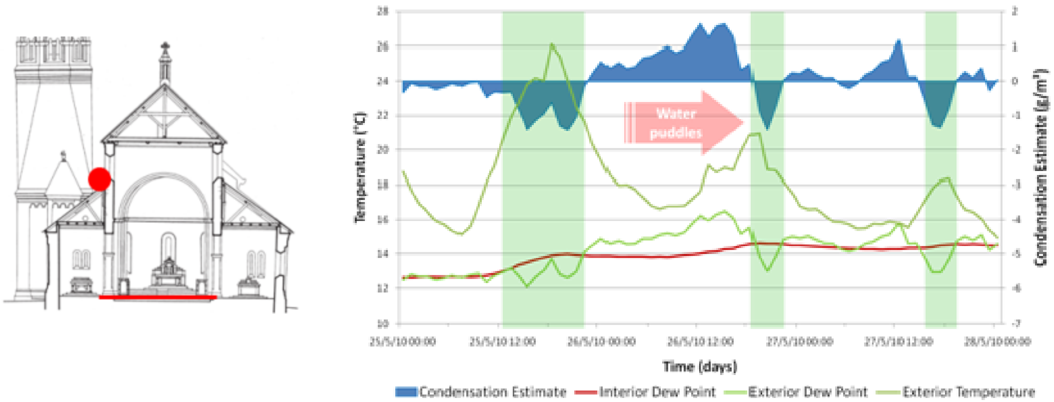

Figure 4. Dew point analysis and condensation estimate at the ground floor level of a church, at which under certain climate conditions water puddles formed on the slab.

An example of a simple analysis routine is shown in **Figure 4**, at which real monitoring data was analysed for estimating condensation risk scenarios inside a church [3]. Based on such a real-time analysis of dew-point temperatures and a condensation estimate, resulting actions like natural ventilation by controlled opening of doors and windows can be supported.

In general such a risk indexes aim can be referred to building microclimate or specific materials or structures characteristic. Considering monitoring parameters as input values of theoretical models or using them for the definition of microclimate maps allows calculating risk indexes. Also, defining several thresholds, warning levels could be determined with the aim to prevent irreversible deterioration by specific restoration operations, adjusting of BMS (Building Management System) settings, need of specific audit or monitoring campaign, maintenance/replacing of building or technological plants components. Furthermore, trials data could also inform about the operation schedule of air conditioning systems and as long as environmental conditions remain stable it is possible to reduce operating hours of the air conditioning, reducing as well the energy consumption.

An important aspect is to know and to understand the impact of the environment to the object and the materials it is composed of. Thus, the application of appropriate models is recommended, which can be applied for preventive conservation monitoring, focussing on environmental causes, materials and their deterioration, microclimate, transport processes and structural behaviour.

A big advantage of the continuous monitoring is that on the one hand the models can be calibrated with real data, and, which is very important in regard to predictive maintenance and prognosis, can be continuously adjusted [8].

CONCLUSIONS

Wireless sensor networks providing autonomous and reliable operation could enormously reduce the costs for structural health monitoring to just a few percentage of a conventional cabled monitoring system. This will increase its application and thus more detailed information could be obtained from the structural behaviour as well as the actual condition of the building structure. Engineers will be enabled to use more precisely information for the structural analysis and repair as well as life time prediction. For that reason first reliable wireless monitoring systems and promising distributed computing strategies are needed. By determination of alarm levels and implementation of permanent self-monitoring, intelligent monitoring systems could operate autonomously for most of the time. However, still a lot of work has to be done. Reliability especially with respect to long-term monitoring is still challenging and the high complexity in customizing and assembling monitoring systems is in contrast to easy handling, usability and ongoing standardisation. Nevertheless one can formulate further design criteria that have to be taken into account:

- Specify data transfer success rate and consider methods to handle possible data loss,
- define data acquisition reliability and provide methods to check data reliability,
- Provide methods to detect also critical temporary events and provide power efficient solutions for that,
- assure autonomous operation and allow remote control and reprogramming,
- provide system ruggedness,
- provide analysis methods to draw interpretable conclusions from continuous monitoring and try to automatise these analysis methods to reduce the amount of data.

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