A hybrid wireless sensor network for acoustic emission testing in SHM

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ABSTRACT

Acoustic emission techniques (AET) have a lot of potential in structural health monitoring for example to detect cracks or wire breaks. However, the number of actual applications of conventional wired AET on structures is limited due to the expensive and time consuming installation process. Wires are also vulnerable to damage and vandalisms. Wireless systems instead are easy to be attached to structures, scalable and cost efficient.

A hybrid sensor network system is presented being able to use any kind of commercial available AE sensor controlled by a sensor node. In addition micro-electro-mechanical systems (MEMS) can be used as sensors measuring for example temperature, humidity or strain. The network combines multi-hop data transmission techniques with efficient data pre-processing in the nodes. The data processing of different sensor data prior to energy consuming radio transmission is an important feature to enable wireless networking. Moreover, clusters of sensor nodes are formed within the network to compare the pre-processed data. In this way it is possible to limit the data transfer through the network and to the sink as well as the amount of data to be reviewed by the owner.

In particular, this paper deals with the optimization of the network to record different type of data including AE data. The basic principles of a wireless monitoring system equipped with MEMS sensors is presented along with a first prototype able to record temperature, moisture, strain and other data continuously. The extraction of relevant information out of the recorded AE data in terms of array data processing is presented in a second paper by McLaskey et al. in these proceedings. Using these two techniques, monitoring of large structures in civil engineering becomes very efficient.

Keywords: Structural Health Monitoring, Wireless Sensor Networks, Acoustic Emission, MEMS

1. MOTIVATION

Continuous structural health monitoring could provide data from the inside of a structure to better understand its structural performance and to predict its durability and remaining life time. In Europe, many structures originate from the middle of the last century, replacing structures destroyed during the Second World War. Concrete structures are typically designed for a 50- to 100-year life. This problem becomes even more evident at railway bridges that are confronted with increasing axle loads and higher train speeds that already very often exceed the structure is for. In this context a European Research Project was approved in the Sixth Framework Program [Sustainable Bridges 2007] where, among others, the Department of Non-destructive Testing and Monitoring of the University of Stuttgart was involved. One objective of the project was to provide monitoring techniques that could help the bridge owners to specify the real structural behavior of their bridge stock.

In particular, structures need a monitoring and inspection procedure which is reliable and inexpensive and easy to implement. The techniques used should be easy to adapt to different types of structures and structural parts since a large variety exists and adaptation is time consuming. From this background the authors strongly recommend the development and application of wireless techniques based mainly on the use of micro-electromechanical systems [Glaser et al. 2005]. A wireless monitoring system equipped with competitive sensors could reduce these costs dramatically. One objective of monitoring civil engineering structures is to detect failure of the structure or moreover of structural parts that reduce the load bearing capacity or the remaining lifetime. The detection and localization of steel tendon failure or concrete cracking in bridge constructions are some examples of a monitoring task.

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Finally, not only existing buildings are subjected to monitoring but also the construction process itself. Previously the contractor simply implemented a given design, but the current trend is for clients to commission certain performance requirements to be met with performance-based design. The emphasis of the industry is becoming the delivery of certain structural behavior states rather than simply building to a client’s plan. The contracting process becomes the determination of the performance criteria, and delivery becomes a long-term fulfillment of these criteria. This can only take place if the performance states can be measured, and the measurement utilizes in a decision making process. The tools needed for both the evaluation of the delivery after construction and during operation are changing accordingly. The process is increasingly dependent on sensor data, valid models to turn the data into physical behavior and decision making tools to determine whether the performance requirements are being met. Regarding proper sensing techniques there are new aspects of measuring structural performance and convert sensor data into useful information needed by stakeholders.

2. WIRELESS MONITORING TECHNIQUES BASED ON MEMS

Existing monitoring systems use traditional wired sensor technologies and several other devices that are time consuming to install and relatively expensive (compared to the value of the structure). Typically they are using a large number of sensors (i.e. more than ten) which are connected through long cables and will therefore be installed only on a few structures. A wireless monitoring system with MEMS sensors could reduce these costs significantly [Grosse et al. 2004; Glaser 2004 and 2005]. MEMS are small integrated devices or systems combining electrical and mechanical components that could be produced for about 50 € each or less. The principle of such a system is shown in the scheme given in Fig. 1.

Figure 1: Scheme for wireless sensing of large structures using radio frequency transmission techniques and MEMS. Data is sent from the base station to the supervisor by using e.g. internet or SMS protocols

2.1 Mote concept
Currently, a wireless sensor node with MEMS sensors could be fabricated at a price varying from 100 to about 400 € and future developments show the potential for prices of only a few Euro. Monitoring systems equipped with MEMS sensors and wireless communication can reduce the costs to a small percentage of conventional monitoring systems, and will increase its field of application. Due to the detailed information of the structural behavior of bridges obtained from the monitoring system, maintenance costs could also be reduced, since inspection methods [Grosse et al. 2005a] can be applied more efficiently. Only after certain changes in the structural behavior have been identified, inspection (either by means of non-destructive testing [Grosse et al. 2005b] or visual methods) will be necessary, and proper repair could be done immediately after the occurrence of the defect. This reduces the risk of further damage.
The analysis of measured data and the knowledge of continuous changes of structural behavior will improve the life time prognosis of civil structures and reduce the overall maintenance costs of buildings and transport networks. Data has to be continuously transmitted (e.g. using the internet or SMS protocols) to the supervisor. Each sensor device (sensor node), which is itself a complete, small measurement and communication system, has to be powered and cost optimized. Using multi-hop techniques, the data of the sensor network can be transmitted over short distances of some 10 m each hop to a base station on site. If the data is a waveform vector rather than pseudo-static scalars, the number of hops becomes limited due to the effect that a certain amount of data might overwhelm bandwidth. Therefore, the aggregation of the data down to a few meaningful values is required. At the base station the data items are collected and stored in a database for subsequent analysis. This data can then be accessed by a remote user. If the central unit detects a hazardous condition by analyzing the data, it raises an alarm message. The central unit also allows for wireless administration, calibration and reprogramming of the sensor nodes in order to keep the whole system flexible. Each mote is composed of one or more sensors, a data acquisition and processing unit, a wireless transceiver and a battery power supply (Fig. 2, right) [Krüger et al. 2005]. The acquisition and processing unit usually is equipped with a low power microcontroller offering an integrated analogue to digital converter (ADC) and sufficient data memory (RAM) to store the measurements. This unit also incorporates signal conditioning circuitry interfacing the sensors to the ADC. In the following sections, some components are described in a more detailed way; see also Krüger et al. [2006].

The entire monitoring system, which has to be installed on site, has to withstand rough environment. For example, it has to be resistant against oil, fuel, salt, alkali and other chemicals. Thus sensors have to be robust and durable so that their measured data is reproducible and reliable over the monitoring lifetime. Furthermore, the system stability, which includes the wireless data transfer to and from the sensor nodes, must be high.

![Figure 2: Principle of a mote. Left: Mote including sensor and data processing board, radio transmission unit, antenna and container. Right: Concept of the sensor and data processing board](image)

### 2.2 Power supply

A structural health monitoring system in civil engineering is supposed to work for long periods of time, e.g. for several months or years, and the size of a mote is not as important as in other applications (e.g. medicine). In order to achieve maximum life, an effective power supply has to be chosen considering a maximum average power consumption of about 2 mW. Due to these power constraints communication should be restricted to as few data as possible and duty cycle has to be optimized. In contrast, computation is much more energy efficient and large amounts of energy can be saved if computation is substituted for communication. Therefore, the mote has to locally pre-process the measurement data and extract relevant parameters. Then only a few bytes describing the signal characteristics have to be sent to the base station.

### 2.3 Sensors

There are different alternatives to obtain data related to the status of a structure. To achieve a long working time of the sensing unit, passive sensors seem to be the best choice. They do not require electric power, because they obtain their energy directly from the change of physical quantities. Piezoelectric materials are an example of such materials. But active sensors could also be of interest, although they require additional electric power to work properly. Most
MEMS sensors incorporate signal conditioning circuitry and/or A/D-converters and therefore require additional electric power. However, MEMS sensors are not available for all kind of applications regarding structural health monitoring in civil engineering. Therefore, sensor nodes are developed to enable motes to communicate with conventional sensors as well, i.e. in addition to MEMS. These sensing techniques are called hybrid sensor nodes. Although these sensors are low-power sensors, they will partly be replaced by MEMS as soon as they are available. Hybrid motes combining sensor systems using different measuring concepts (active or passive sensing, piezos, active fibers, MEMS and so on) can be designed to optimize the data acquisition and to best fit the in-situ requirements. Based on our mote developments a strain-gage hybrid sensor system was developed. Some other physical properties to be measured in-situ are the vibrations of the structure, humidity and temperature outside and inside the structure, stress and strain, and the detection of crack growth and other deterioration. A concept of using acoustic emission techniques for crack growth detection is discussed in the second paper by McLaskey et al.

2.4 Combined sensor information and clusters of motes
It is expected that the correlation of the recorded AE data with the other data obtained by each sensor (temperature, humidity, strain, etc.) will lead to further understanding of structural behavior. For example a cross-check of AE activity with increasing strain or with a sudden or abnormal increase of the ambient or inner structure temperature can give further insight into structural state. Such sensor data correlations will also decrease the amount of data transmitted after implementing intelligent data processing and correlation algorithms. Data analysis techniques based on the signal wave form should be checked carefully prior to any developments. To give an example it is recommended to minimize the data transfer through the radio module which means that signal processing and data analysis should be done in the sensor mote as far as possible. However, the signal analysis could be made by software or a DSP or FPGA. In addition to the local signal processing running on a single mote, information within clusters can be aggregated in intermediate nodes, further processed, and forwarded as needed in compound packets to save energy. First storing a set of data in a given sensor mote and then sending it consecutively through the radio module at specific time intervals, or events on request, will also improve the reliability of data transfer because the transfer can be specifically controlled. The need for cluster formation and management is also motivated by power consideration concerns as well as by the necessity of deciding whether or not an event is related to a structural defect or change in structural behavior. These clusters need to organize themselves and determine the cluster head based on the current conditions of the network.

3. SENSOR NETWORKS AND PROTOCOLS

Wireless sensor networks consist of many nodes (motes) having one or several different sensors on board. After the recording and a preliminary analysis of the data in the mote, the data has to be transmitted using, for example, a radio transmission system to a base station or supervisor for further data processing or proper generation of alarm messages. For the transmission of data using sensor nodes in a network of motes several topologies exist including the star and the multi-hop topology [Culler et al. 2003].

Figure 3: Scheme of a multi-hop sensor network using clustered sensor nodes
The main advantage of multi-hop techniques are the transmission power efficiency, because only a fraction of energy is necessary to transmit data compared to other techniques; the data are transmitted just to the neighbour nodes and not necessarily to the sink. This reduces also the danger of interference since a node communicates only with a few others. However, this requires sophisticated network protocols including ad hoc configuration capabilities as well as self-configuration, calibration and encryption. As a next step we will implement a clustered multi-hop technology. Motes in a cluster (marked with a dashed circle in Fig. 3) share the data of all sensors attached to these motes. A pre-processing of the data is done in the cluster prior to transmission via the other clusters in the multi-hop network to the data sink (symbolized by the laptop in Fig. 3). This is the main advantage compared to telemetric systems where all data are transmitted. Intelligent data processing in the motes or clusters enables pattern recognition algorithms, which can additionally reduce the power consumption. Only meaningful data are transmitted to the sink. The data sink is further extracting information out of the data using knowledge-based algorithms sending afterwards the information to the responsible person (construction engineer, owner) using automated email messages or short message systems to mobile phones.

A sensing system based on wireless motes has several more advantages. Such a system is easy and cost efficient to be applied to structures. It can be used on one structure for a while and when or if the stakeholder decides to have enough data collected at this particular structural part the system can easily be deployed somewhere else. Additionally, a variety of sensors can be used to get information about the status of the structure. It is obviously very helpful not to base a structural health analysis on one physical quantity alone or on one sensor. The reliability of a monitoring system is fairly enhanced combining the information obtained at different sensor nodes as described in the above section. Further on, comparison of time series acquired by recording different physical quantities results in a drastic improvement of reliability and lowers the detection threshold of deterioration. Establishment of a correlation between data and structural performance is difficult and should be based on the data interpretation expertise of the user, implying a natural application of Bayesian statistics. Embedding some local processing capabilities within the sensor networks is desirable. For example, the temperature data gathered from numerous sensors could be fed into one or more other sensors on the network for processing. A weighted average could then be calculated and transmitted to the user, significantly reducing the amount of data flying around the network.

Finally, two other advantages of wireless sensor networks have to be stressed. Scalability can be an issue if the stakeholder wants to extend the monitoring area or need more data. Existing WSN techniques enables for self-organization of such networks so that sensor nodes can be added or removed at any time without time consuming user guided reorganization of the WSN. Additionally, the implemented pre-processing algorithms might need an update from time to time to adjust to the user requirements or for a more efficient data reduction. Most of the developed sensor nodes have the capability to be reprogrammable, i.e. that the user can change the algorithms implemented in each sensor with pressing a button.

4. HARDWARE DEVELOPMENTS

Separate boards for signal conditioning of strain and piezoelectric data (like acoustic emissions) have been developed by the University of Stuttgart partly with the help of EMPA (Eidgenössische Materialprüfungs- und Forschungsanstalt, Switzerland). Implementation and development of the electric components, layout as well as manufacturing of prototypes is in progress. The boards are developed for rough environment what include the implementation in sealed containers following the IP64/65 standards of water protection.

As an energy source a high capacity 18 Ah battery was chosen at this stage of the project keeping in mind that it should be replaced by other techniques (solar power, energy harvesting techniques) depending on the application. In addition to strain and vibration data, ambient temperature and humidity can be measured by MEMS sensors implemented in the motes. A signal conditioning board for strain gage measurements was developed (Fig. 4) with the option of two parallel strain measurements at the same time. The board enables a full front-end for resistive sensors with temperature compensation using dummy strain gages as well as calibration and zero compensation by software (Fig. 4, right).
Also a signal conditioning board (Fig. 5) for piezoelectric sensors (i.e. AE sensors) was developed consisting of two channels per board with the opportunity to implement two boards in one sensor node. Each of the 4 channels can be filtered and amplified individually. Amplification can be chosen between 100-fold and 1000-fold. Userspecific antialiasing filters (and usually have to be) be applied and a triggered recording of events is possible using a programmable comparator. Several operation modes to reduce the energy consumption are implemented as well. The board can be switched off completely by software. The A/D conversion is done using the TI microcontroller MSP430 from the mote. It allows for an A/D conversion with 12 bit resolution at sample rates of up to 100 kHz, depending on the number of active channels. The number of samples, that are recorded after the detection of an event is configurable, as well as is the pretrigger and the threshold for the analog comparator. For performance reasons, the MSP430's DMA capabilities are used for transferring the sampled data to internal memory. In active mode, samples are stored to a circular buffer until the trigger interrupt is set off. The remaining samples of interest are then recorded and afterwards the sampling stops for the time of data transmission. Comfortable user interfaces (GUI) were developed to control the devices. For first tests only one channel was used for acoustic emission (AE) monitoring.

Figure 4: Signal conditioning board for strain and developed graphical user interface for calibration

Figure 5: Mote consisting of a processor board with 4-channel signal conditioning for acoustic emission analysis (left) and industrialized sensor node prototype attached to a reinforced concrete structure for crack monitoring (right)
5. MONITORING BRIDGES USING WIRELESS SENSING TECHNIQUES

As a first test the equipment was installed for wireless measurements of strain and acoustic emissions during load at a large test facility (Fig. 7) of the Technical University of Braunschweig, Northern Germany, and at a smaller structure of the University of Stuttgart. Detailed results on that are reported in Grosse et al. [2007a]

![Figure 7: “Concerto Bridge” in Brunswick equipped with wireless AE sensors (left) and with wireless strain sensors (right)](image)

The primary tasks of an implemented AE system in WSN consists of signal detection, denoising, localization and other data analysis and signal characterization techniques as described in the papers by Grosse et al. [2007b] or in the paper by McLaskey et al. in these proceedings. However, the interpretation will presumably be limited to an indication of a “zone of interest” further investigated by methods developed in and interpretation techniques based on results of ongoing work. It is expected that the correlation of the recorded AE data with the data obtained by each sensor (temperature, humidity, strain, etc.) will lead to further understanding of structural behavior. For example a cross-check of AE activity with increasing strain or with a sudden or abnormal increase of the ambient or inner structure temperature can give further insight into structural state. Such sensor data correlations will also decrease the amount of data transmitted after implementing intelligent data processing and correlation algorithms.

6. GENERAL ASPECTS OF DATA ANALYSIS FOR WSN

Fig. 8 shows the hardware setup as well as the stepwise analysis procedure for interpreting the acquired data considering low power consumption. The procedure starts with the in-mote detection and signal analysis followed by a cluster analysis and at least a structural analysis. The analysis techniques could include an updating of the implemented models as well as the data used for comparative analysis. Therefore, the sensor network could become a neural network.

![Figure 6: Analogue signal conditioning with interrupt generation (right: prototype circuit board)](image)
7. CONCLUSIONS

The inspection of building structures is currently a visual process. Therefore, the condition of the structure is examined from the surface and the interpretation and assessment is based on the level of experience of the engineers. An approach to continuous structural health monitoring techniques based on wireless sensor networks were presented, which provide data from the inside of a structure to better understand its structural performance and to predict its durability and remaining life time.

Structural health monitoring (SHM) deals with the more or less continuous recording of data obtained from several parts of the structure. Based on the experience of the constructor, owner, or inspector the regions where data are obtained can be restricted. In many cases it is necessary to just detect a deviation of the “usual” behavior of the structure, i.e. an outlier in a time-series. It is obviously very helpful not to base this analysis on one physical quantity alone or on one sensor. The reliability of the monitoring system is fairly enhanced combining the information obtained at different sensor nodes. Further on, comparison of time series obtained by recording different physical quantities results in a drastic improvement of reliability and lowers the detection threshold of deterioration. Establishment of a correlation between data and structural performance is difficult and should be based on the data interpretation expertise of the user, implying a natural application of Bayesian statistics. This combination can be done even in terms of a pre-processing of data in the mote or in a cluster of motes. This is the main advantage to telemetric systems using all the data. Intelligent data processing in the motes or clusters enables pattern recognition algorithms which can additionally reduce the power consumption. Only meaningful data are transmitted to the sink.

Acoustic emission techniques can play a significant role for the monitoring of civil engineering structures since they are able to detect reveal hidden defects leading to structural failures long before a collapse occurs. However, most of the existing AE data analysis techniques seem not be appropriate for the requirements of a wireless network including distinct necessities for power consumption. The authors suggested approaches using array techniques. First tests showed promising results and are summarized in the paper by McLaskey et al. in these proceedings.
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6. REFERENCES


