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Condition monitoring of concrete structures using wireless sensor networks and MEMS

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ABSTRACT

The inspection of building structures, especially bridges, is currently made by visual inspection. The few non-visual methodologies make use of wired sensor networks, which are relatively expensive, vulnerable to damage, and time consuming to install. Systems based on wireless sensor networks should be both cost efficient and easy to install, scalable and adaptive to different type of structures.

Acoustic emission techniques are an additional monitoring method to investigate the status of a bridge or some of its components. It has the potential to detect defects in terms of cracks propagating during the routine use of structures. However, acoustic emissions recording and analysis techniques need powerful algorithms to handle and reduce the immense amount of data generated. These algorithms are developed on the basis of neural network techniques and – regarding localization of defects – by array techniques. Sensors with low price are essential for such monitoring systems to be accepted. Although the development costs of such a system are relatively high, the target price for the entire monitoring system will be several thousands Euro, depending on the size of the structure and the number of sensors necessary to cover the most important parts of the structure.

Micro-Electro-Mechanical-Systems and hybrid sensors form the heart of Motes (network nodes). The network combined multi-hop data transmission techniques with efficient data pre-processing in the nodes. Using this technique, monitoring of large structures in civil engineering becomes very efficient including the sensing of temperature, moisture, strain and other data continuously. In this paper, the basic principles of a wireless monitoring system equipped with MEMS sensors is presented along with a first prototype.

The authors work on details of network configuration, power consumption, data acquisition and data aggregation, signal analysis and data reduction is presented.

Keywords: Monitoring, wireless sensor networks, structures, concrete, MEMS, acoustic emission

1. MOTIVATION

Continuous structural health monitoring should provide data from the inside of a structure to better understand its structural performance and to predict its durability and remaining life time. In particular acoustic emission (AE) measurement will be examined due to its ability to warn of crack growth and its mode. For example, railway bridges must contend with higher axle loads and higher train speeds [Sustainable Bridges 2006] than expected during construction. Another example are structures exceeding the designed 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 80-year life, which will soon be reached. The sudden collapse of a training hall in Bad Reichenhall (Germany) in early January 2006 with the loss of 15 lives and the collapse of a new trade building in Katowice (Poland) several weeks later – more than 60 lost their lives – demonstrated these problems drastically.
This leads to the conclusion that 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

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structural parts since a large variety exists and adaptation is time consuming. From this background the authors strongly recommend development and application of wireless techniques based mainly on the use of micro-electromechanical systems [Glaser et al. 2005].

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 (Micro-Electro-Mechanical-Systems) sensors could reduce these costs significantly [Grosse et al. 2004a; Glaser 2004 and 2005]. MEMS are small integrated devices or systems combining electrical and mechanical components that could be produced for about 50 € each. The principle of such a system is shown in the scheme given in Fig. 1.

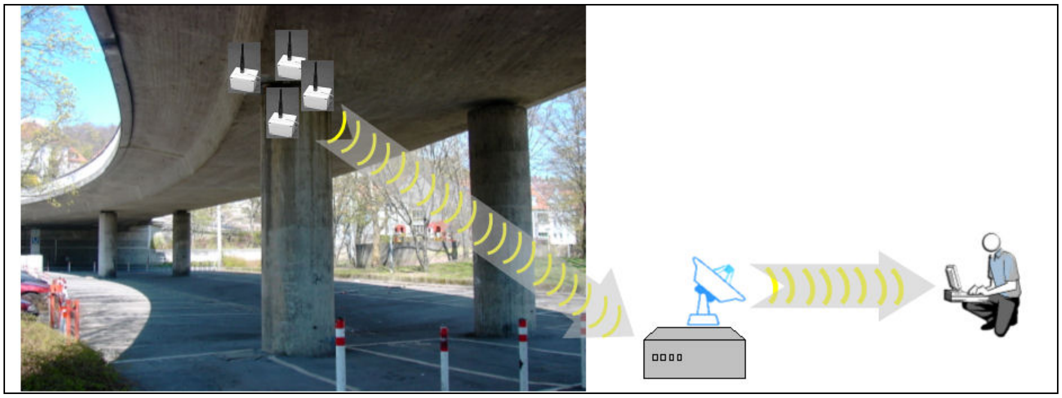


Figure 1: Scheme for wireless sensing of large structures using radio frequency transmission techniques and MEMS [Grosse et al. 2004]. Data are sending from the base station to the supervisor using e.g. internet or SMS protocols

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, will inspection (either by means of non-destructive testing [Grosse et al. 2005b] or visual methods) 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 (mote), 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 then pseudo-static scalars, the number of hops becomes limited due to an additive effect, which quickly overwhelms bandwidth.) 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 mentioned, but a more detailed description is given elsewhere [Krüger et al. 2006].

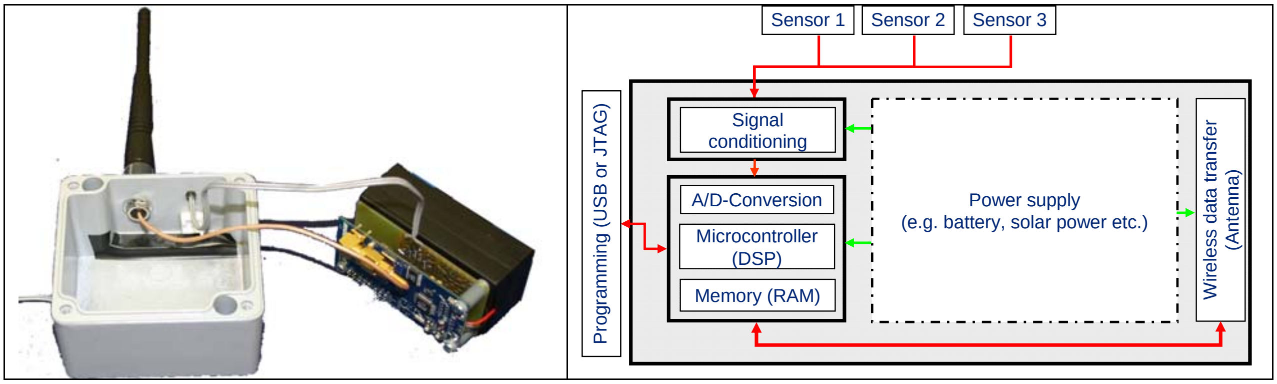


Figure 2: Principle of a MEMS based “mote”. Left: Mote (© Smartmote) including sensor and data processing board, radio transmission unit and antenna, container. Right: Concept of the sensor and data processing board

2.1 Power supply

A structural health monitoring system 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 and a mean power consumption of about 2 mW maintained. Due to these power constraints communication should be restricted to as few data as possible. In contrast, computation is much more energy efficient and large amounts of energy can be saved if communication 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.

2.2 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. 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 (Fig.2, left). Some 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 next section. It is necessary to divide monitoring into discrete and event based monitoring, which is similar to data recording on request event based data aggregation.

The entire monitoring system, which has to be installed on site, has to withstand rough conditions (climatic and other types). 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.

2.3 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].

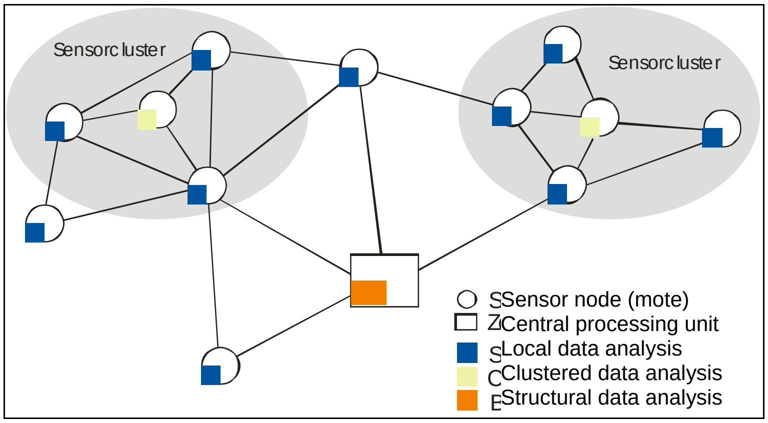


Figure 3: Scheme of a multi-hop sensor network using clustered sensor nodes [Krüger et al. 2006]

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 next 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 [Saukh et al. 2006] including ad hoc configuration capabilities as well as self-configuration and calibration.

Special attention to time synchronisation is needed if measured values are compared. This is in particular necessary for acoustic emission techniques in a clustered sensor network. The required time accuracy is in the order of milliseconds or even microseconds and only achievable using complex algorithms [Estrin et al. 2002].

3. DATA ANALYSIS

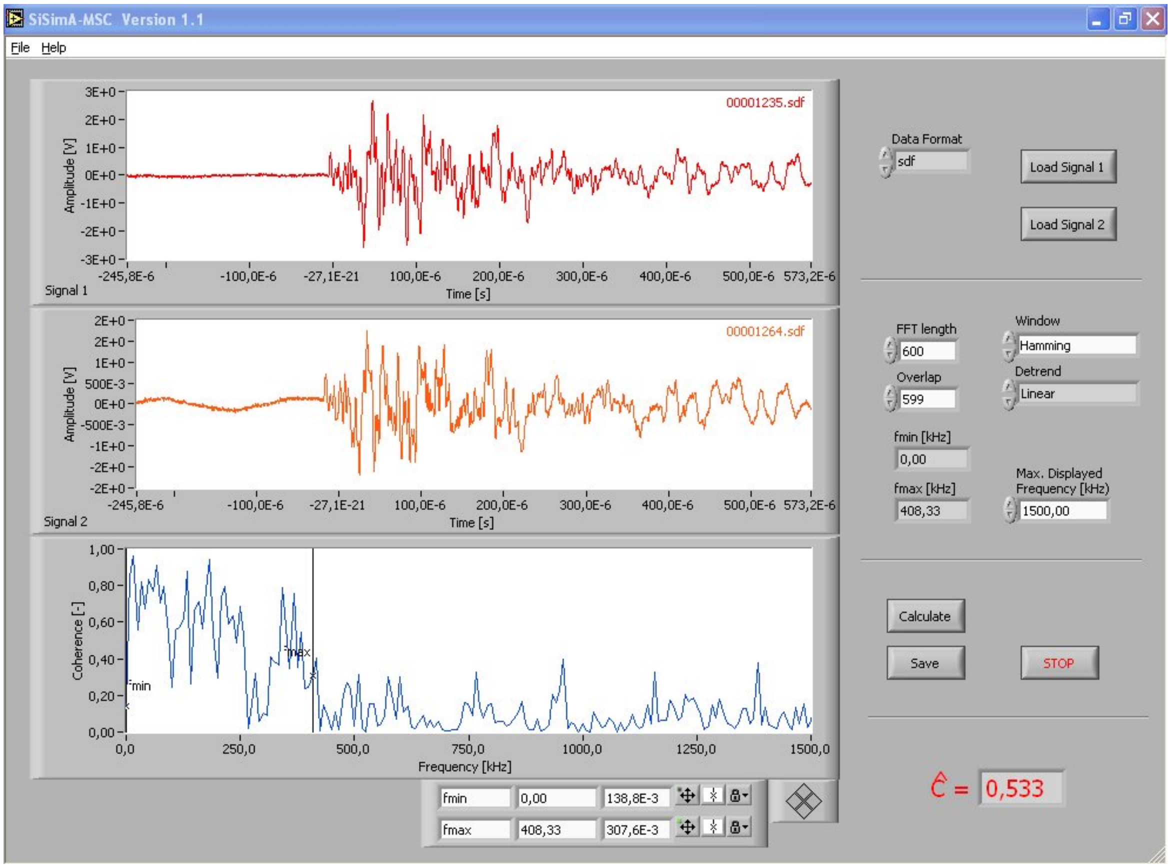
Structural health monitoring (SHM) deals with the more or less continuous recording of data obtained from several parts of the structure. Based on the experience of the constructor, owner, or inspector the regions where data are obtained can be restricted. In many cases it is necessary to just detect 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.

3.1 SHM using combined sensor information and clusters of motes

It is expected that the correlation of the recorded AE data with the data obtained by each sensors (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 will be included in future (e.g. [To & Glaser 2005]; [Ching et al. 2004]). Algorithms have been developed regarding energy-based techniques and techniques analyzing signals in the frequency/time, frequency/wavenumber or wavelet/time domain. Implementation of these techniques in motes must account for digital recording techniques, the sensor characteristics and the coupling of the devices to the structure, as well as power consumption. The feasibility of mote implementations 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 that can perform a 1024-point FFT at 3.1 µJ using a 1.1 V supply.

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. Such data aggregation and data reduction methods are needed to minimize the data traffic if the monitoring system consists of a high amount of motes. 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.



Data Format: sdf

FFT length: 600

Overlap: 599

Window: Hamming

Detrend: Linear

fmin [kHz]: 0,00

fmax [kHz]: 408,33

Max. Displayed Frequency [kHz]: 1500,00

fmin	0,00	138,8E-3
fmax	408,33	307,6E-3

$\hat{C}$ = 0,533

Figure 4: Example of similarity analysis techniques. Signal 1 (upper graph) is similar to the second signal (middle) and the MSC analysis (bottom) results in a fairly high similarity value $\hat{C}$ of 0.533 [Grosse et al. 2004b]

3.2 Acoustic emission techniques for structural health monitoring

The most common passive monitoring system involves acoustic monitoring, most commonly called acoustic emission (AE). Acoustic emissions are elastic waves generated in conjunction with energy release during crack propagation and internal deformations in materials. Micro-structural changes or displacements occur very rapidly and can be produced by a wide variety of material responses to stress changes, from small scale changes within a crystal lattice structure to growth of macro-cracks. As stress waves propagate through a medium, the waveform shape is formed by the characteristics of the source, and affected by properties of the host material, and eventually the geometry of the host medium.

The primary tasks of an implemented AE system in wireless sensor networks consists of signal detection, denoising, localization and other data analysis and signal characterization techniques as described in the following. This document does not details of the data interpretation, because this should follow the first field tests and analysis of first recorded data. 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.

3.2.1 Signal detection

The discrimination between noise and signals (from structure deterioration) is essential for failure monitoring. The environment (railway bridges) is assumed to be very noisy. A noise analysis must be conducted using conventional hardware and sensors (broadband sensors) to characterize the frequency bands of noise at different bridges. This could be done during field tests at concrete, masonry and steel bridges separately.

Algorithms to discriminate between signal and noise have to be developed and to be implemented into the motes. It is assumed that the AE signal form is governed by travel path effects which overpower signals from the fracture process, enabling for simple discrimination techniques.

a. Cross-correlation: Laboratory tests showed that the cross-correlation of signals originating from similar parts of a structure show a high correlation. Based on detailed knowledge of the structure, certain regions can be monitored directly by storing in memory the values of cross correlation between the actually recorded signal and a reference signal which is permanently stored in the (EPROM) called "signal squared coherence" (Fig. 4), giving a simple figure of signal similarities [Grosse et al. 2004b]. Only the correlation coefficient (coherence value), the event time and the "name" of the mote recording it have to be transmitted wirelessly. In the central processing unit a correlation of these data with real coordinates can be done. If several "hits" are recorded an alarm message can be transferred to the operator. Another approach is based on the "Sonogram analysis" [Joswig et al. 2002] including a pattern recognition algorithm for a multi sensor seismic array. The sonogram of the recorded signal can be compared to a simple predefined pattern.

b. Using the noise characteristic onsite as well as the amplitude attenuation due to geometrical spreading, a simple frequency transform can be used to discriminate signals from noise. This technique can be combined with simple threshold triggers and the method described under a.

3.2.2 *Denoising*

If AE signals are significantly affected by electronic or other noise, procedures called denoising have to be applied. Unfortunately, these techniques are usually calculation intense and therefore increase power consumption. Simple denoising techniques include bandpass filtering prior to data analysis. This can be done using proper hardware. If this is not sufficient, more sophisticated wavelet based filters can be applied which are under development [Grosse et al. 2002]. These developments optimize the code in terms of power consumption. Another (probably more promising) options are methods based on array techniques which are described in section 3.3.

3.2.3 Waveform Analysis

The wave motion transmitted by AE through the host medium contains information about the location and kinematics of the deformation (i.e. damage) taking place inside. By transducing and recording a suite of unadulterated particle motions in a three dimensional array relative to the internal dislocation, inversion theory can be used to identify the source kinematics [Stump & Johnson 1977; Ching & Glaser 2000]. The fidelity of the sensor used is critical to quantitative AE analysis since the strain history must be accurately transformed into an electronic signal for any meaningful analysis to be carried out. Quantitative interpretation of AE signals start from a simple location of the internal source of the AE, such as fracture or perhaps the relative motion of rebar and concrete. Simply using unambiguous first arrival of the primary (and/or secondary wave) can provide source kinematics through moment tensor inversion (e.g. [Fink et al. 2003]; [Carvalho & Labuz 2002]; [Grosse et al. 1997]). Finally, an initial length of the waveform - from primary wave to surface wave arrival - can be used to perform a higher order inversion to yield full source kinematics (e.g. [To & Glaser 2005]; [Sachse et al. 1984]). These techniques allow the user to qualitatively “peer into” the structure being monitored and identify the damage taking place to determine the actual condition so that preventative maintenance can be rationally applied.

3.2.4 Localization

There are diverse techniques for AE localization using completely different algorithms and assumptions. It is essential to know all existing solutions and to apply the most appropriate. For this reason a rough compilation of existing methods should follow. More details can be obtained from the literature in preparation [Ohtsu & Grosse 2006]

a. The roughest localization method is guessing the source origin using the “first hit” technique. The advantage of first hit techniques is that no sensor arrays and no data analysis are necessary. The sensor which detects one of several AEs first defines a radius or a half sphere, respectively, in which the signal originated. Experience tells whether that technique is accurate enough. This can be done for some cases probably in combination with techniques described under section 3.2.1 or with knowledge from bridge inspectors to “localize” the source of failures.

b. More sophisticated methods use planar techniques by recording AE signals at more than two sensors at the same time. This method requires time synchronization of the motes and communication between motes. More suitable techniques are beamforming for localization, described in section 3.3. It should be stressed that 2D and even 1D localization can work well when used together with a priori information obtained from the construction plans or from the inspector of the bridge.

c. Traditional 3D-localization techniques [Grosse et al. 2003; Ohtsu & Grosse 2006] are not implemented in wireless sensor networks because of processing time and power consumption from inter-array communications. In many cases, the signal-to-noise ratio is not good enough to apply 3D-localization.

Since sensor arrays are common in seismology, array data analysis techniques were implemented in the motes. These techniques are now under test, requiring only data communication between motes in a cluster. The transmission of alarm data to the sink can be restricted to the source coordinates and the time of the event if necessary. An advantage of this technique is that time synchronization between two motes is less important.

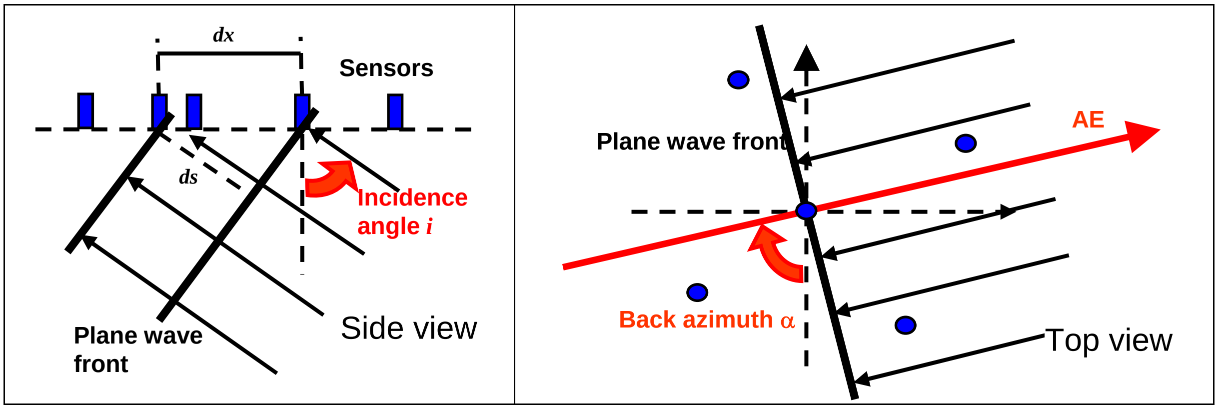


Figure 5: Example for the derivation of basic measures in array localization using five sensors (in this example) and a plane wave hitting the array under the incidence angle *i* and with the back azimuth α.

3.3 Array techniques

A further step to apply acoustic emission analysis to wireless sensor networks is the implementation of beamforming techniques. Beamforming can be used to improve the signal-to-noise ratio of direct compression waves from known sources. It can further on be used do detect certain coherent signal phases if two or more are crossing the array and have to be discriminated. Finally it is useful for a rough localization of events. The principles of array techniques have been first developed for applications in electrical engineering e.g. for antenna or microphone arrays. In seismology, similar techniques were developed for the nuclear test ban treaty to monitor unusual seismic activity possibly originating from underground nuclear explosions. Due to the methodological similarity between acoustic emission analysis and seismology, the assumption is made in both cases that a plane wave arrives at the sensor array. This is the case if the source is far enough away compared to the distance between the sensors.

The signal-to-noise ratio of a signal can be improved by stacking the coherent signals from each sensor after correcting for the different arrival or delay times. Therefore, the most important point during array beamforming is to find the best delay times for shifting the individual signals. One sensor is chosen to be the reference sensor and all parameters are taken relative to this sensor. For an incoming plane wave, the time delays Δt_i observed at sensor i are given by

$$\Delta t_i = \frac{S_i}{v^*} = \frac{1}{v^*}(x_i \sin\alpha + y_i \cos\alpha)$$

where S_i denotes the horizontal distance to sensor i in a x_i, y_i coordinate system. For most applications in civil engineering, sensors are in the same horizontal plane and negligible elevation differences between the sensors can be assumed. In this case, the vertical component z_i of the slowness vector v^* is zero. A detailed description of the slowness can be found in Shearer [1999]. After deriving delay times Δt_i for each sensor for a specific backazimuth α and apparent velocity v^*, the individual traces are stacked to form a so-called array beam using the “delay and sum technique”. The traces can be amplitude normalized and bandpass filtered before the summation. In Fig. 6 beamforming is used to improve the signal-to-noise ratio of direct compression waves from a known source. The upper trace shows the resulting summed signal improved by an array beam of the eight channels below demonstrating how the signal-to-noise ratio can be increased during beamforming. A simple stack of n traces (n sensor data) suppresses incoherent (random) noise by a factor of $\sqrt{n}$. Some sort of weighted stacking [Kennett 2000] can further improve the signal-to-noise ratio.

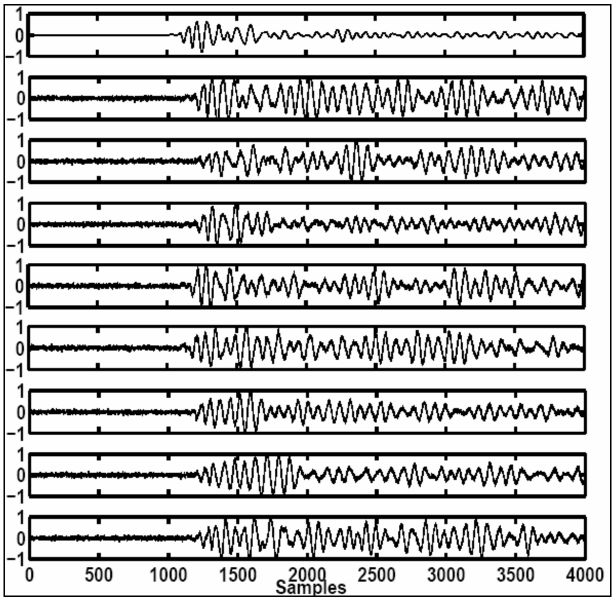


Figure 6: Example of the delay and sum method stacking eight signals to form a beam to the first arrival phase. The result is a significant improvement of the signal-to-noise ration in the summed-up signal (first trace).

As shown, this technique can efficiently improve the signal quality, but in general, it can also be used do detect certain coherent seismic phases, or to locate their origin. In this case the goal is to determine the direction and the incidence angle of the approaching plane elastic wave. The direction of a propagating wave can be described using the incidence angle i and the back azimuth α (Fig. 5) which is measured relative to a reference sensor. The components of the slowness vector can be expressed as functions of the back azimuth and the incidence angle. There are basic relations between the incidence angle and the slowness *v** which is again the reciprocal of the apparent velocity of the plane wave crossing the array derived from the time differences *dt*:

$$\frac{dt}{dx} = \frac{\sin i}{v_p} = Slowness\ v^*$$

In the case that each channel (single-sensor recording) of an event is properly shifted in time for a certain back azimuth and slowness, all signals with the matching back azimuth and slowness will sum constructively. Examples of a successful beamforming application for localization are presented elsewhere [Krüger et al. 2006]. If more than one array is used a two-dimensional localization of the source of the incident wave is possible by calculating the point of intersection of at least two back azimuth lines in the plane of the sensor array.

The advantage of such a localization procedure for the use in sensor networks is that no time consuming onset determination is needed. Due to the long travelpath the signals do not have high frequency content any more. Therefore, as first tests showed, the principle works with even low sampling rates. This enables for the use of highly automated and wireless systems which have to work under difficult energy-saving conditions.

As mentioned, beamforming techniques can be applied to discriminate for a certain wave phase. This is useful to detect wave modes hidden by reflected waves or in the coda of a preliminary wave. Applications are the detection of shear wave onsets or reflected waves. For phase detection a 3D iteration problem has to be solved, iterating signal time, slowness, and amplitude. Visual analysis can be done by generating a graph in the slowness-time domain, as shown in Fig. 7 [Grosse 1989]. This example, obtained from data analysis of a seismological array, shows the discrimination between two different types of compression waves which traveled via different raypath, from the source to the receiving array. Out of such a graph it is easy to determine the optimum slowness for the delay and sum method for each phase (wave).

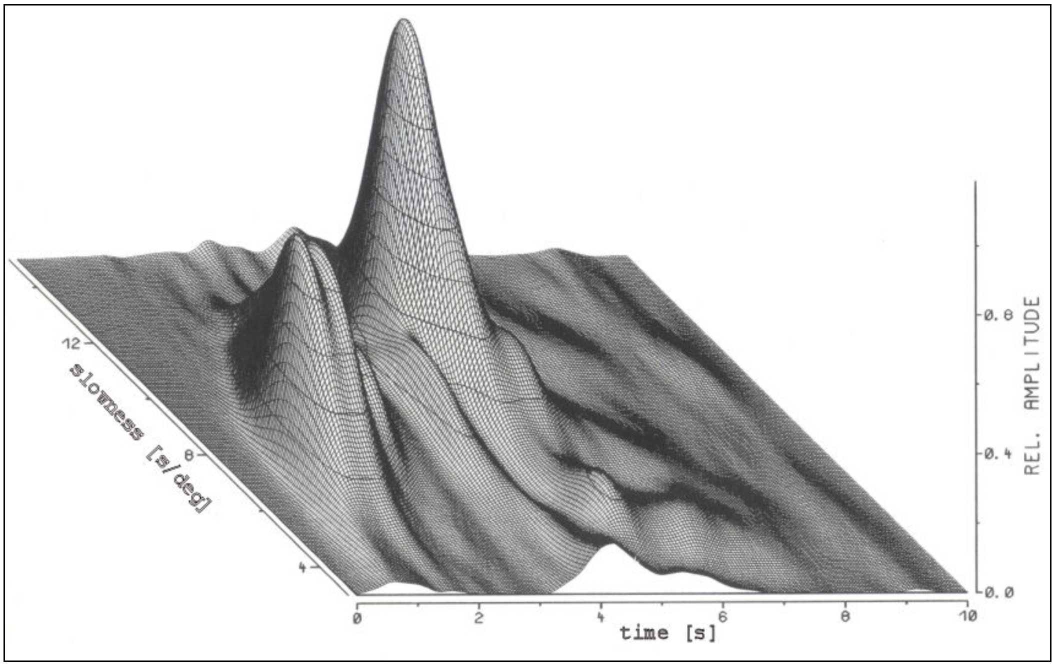


Figure 7: Example of array data analysis in the slowness domain [Grosse 1989].

The application of this method significantly increases onset time reliability, and can help in the localization process or in determination of fracture type [Grosse et al. 2003].

4. 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.

A wireless sensor network system based on MEMS and hybrid sensors is developed by a team of scientists from different institutions (IWB, UC Berkeley, Smartmote). The network is equipped with motes and will be available for a very low budget. Since prototypes are already available, the system is now undergoing an optimization process regarding power consumption, data acquisition and data aggregation, signal analysis and data reduction [Krüger et al. 2006].

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 seems not be appropriate for the requirements of a wireless network including distinct necessities for power consumption. The authors suggested with this paper approaches using array techniques. First tests showed promising results for both, reliable AE data analysis as well as power saving processes. Further developments based on this approach will show the efficiency of the suggested techniques.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

Carvalho, F., and Labuz, J.F. 2002. Moment Tensors of Acoustic Emission in Shear Faulting Under Plane-Strain Compression. *Tectonophysics*, 356, pp. 199-211

Ching, J.-Y., To, A., and Glaser, S.D. 2004. Acoustic Emission Source Deconvolution: Bayes vs. Minimax, Fourier vs. Wavelets, and Linear vs. Nonlinear, *Journal of the Acoustical Society of America*, 115(6), pp. 3048 - 3058**.**

Ching, J.-Y., and Glaser, S.D. 2000. A Time Domain Moment Tensor Inversion Technique and Its Verification, ASCE Geotechnical Special Pub. #102, *Trends in Rock Mechanics*, pp. 140-151

Culler, D., Woo, A., Tong, T. 2003. Taming the Underlying Challenges of Reliable Multihop Routing in Sensor Networks. In: Proceedings of the First International Conference on Embedded Networked Sensor Systems, 2003.

Estrin, D., Elson, J., Girod, L. 2002. Fine-Grained Network Time Synchronization using Reference Broadcasts. In Proceedings of the 5th symposium on Operating systems design and implementation, 2002.

Finck, F., and Manthei, G. 2004. On Near-Field Effects in Signal Based Acoustic Emission Analysis, *Otto Graf Journal*, 15, pp. 121-134.

Glaser, S.D. Some Real-World Applications of Wireless Sensor Nodes, Proceedings, SPIE Symposium on Smart Structures & Materials/ NDE, 2004, San Diego, California, March 14-18, 2004.

Glaser, S. D. 2005. Advanced Sensors for Monitoring Our Environment, Proceedings, 1st International Symposium on Advanced Technology of Vibration and Sound, Miyajima, Japan, 1-3, June.

Glaser, S.D., Shoureshi, R., and Pescovitz, D.2005. Future Sensing Systems, *Smart Structures & Systems*, 1(1), 103 - 120.

Grosse, C. U. Peaceful Nuclear Explosions - PNE's - im Nordkaspischen Becken (UdSSR). Diploma Thesis, Geophysical Institute, University of Karlsruhe, 1989, 116 p.

Grosse, C. U., M. Motz, H.-W. Reinhardt, B. Kröplin: Signal conditioning in acoustic emission analysis using wavelets. NDT.net – The electronic Journal for Non-destructive Testing, September 2002, Vol. 7 No. 9 (2002), 7 p.

Grosse, C. U., H.-W. Reinhardt, F. Finck: Signal-based acoustic emission techniques in civil engineering. J. of Mat. In Civ. Eng. 15 (2003), No. 3, pp 274-279.

Grosse, C. U., F. Finck, J. H. Kurz and H. W. Reinhardt. 2004a. "Monitoring techniques based on wireless AE sensors for large structures in civil engineering", in Proc. *EWGAE 2004 symposium* in Berlin, BB90, pp 843-856. Berlin: DGZfP.

Grosse, C. U., F. Finck, J. H. Kurz and H. W. Reinhardt. 2004b. "Improvements of AE technique using wavelet algorithms, coherence functions and automatic data analysis techniques", J. of Constr. and Build. Mat., 18 (3), pp 203-213.

Grosse, C. U., J. Kurz, R. Beutel, H. W. Reinhardt, M. Krüger, P. J. Marrón, O. Saukh, K. Rothermel, J. Meyer, G. Feltrin. 2005a "Combined Inspection and Monitoring Techniques for SHM of Bridges". International Workshop on Structural Health Monitoring (IWSHM) 2005, Stanford University, Stanford, CA, September 12-14, 2005, Ed: Fu-Kuo Chang; Lancaster PA: DEStech Publications Inc. (2005), pp 1403-1410.

Grosse, C. U., R. Beutel, H. W. Reinhardt, M. Krüger. 2005b: "Impact-echo techniques for non-destructive inspection of concrete structures". Int. Conf. on Conc. Repair, Rehabilitation and Retrofitting (ICCRRR), Cape Town, South Africa, Nov. 2005, Balkema Publ. Rotterdam (eds. M. Alexander et al.), 2005b, pp 174-176.

Joswig, M. Wust-Bloch, H., Leonard, G. Nanoseismology: Development of an integrated technique for the monitoring of nanoseismig events triggered by natural subsurface material failure, Israel Atomic Energy Commission, Report # 2791458, 2002, 26 p.

Kennett, B.L.N. Stacking three-component seismograms. Geophys. J. Int. 141 (2000), 263-269.

Krüger, M., C. U. Grosse and P. J. Marrón. 2005. "Wireless structural health monitoring using MEMS". In: W. M. Ostachowicz et al. (eds). Damage Assessment of Structures, 4th – 6th July 2005, Proc. Intern. Symp., Gdansk, Poland, Zürich: Trans Tech.

Krüger, M., Grosse, C. U. 2006. „Preiswerte Dauerüberwachung von Bauwerken mit drahtloser Sensorik", DGZfP, Fachtagung Bauwerksdiagnose, Berlin, Februar 2006 (in print).

Kurz, J. H., C.U. Grosse and H.W. Reinhardt. 2005. „Strategies for reliable automatic onset time picking of acoustic emissions and of ultrasound signals in concrete", Ultrasonics, 43 (7). pp 538-546.

Ohtsu, M., Grosse, C.U. (eds.): *Basics and Applications of Acoustic Emission Testing in Civil Engineering*. Springer publ., Heidelberg, 2006, ca. 320 p (in preparation).

Sachse, W., Chang, C., and Kim, K. Y. 1984. Processing of AE Signals from Point and Extended Sources, *IEEE Ultrasonics Symposium*, pp. 933-937.

Saukh, O., Marrón, P.J., Lachenmann, A., Gauger, M., Minder, D., Rothermel, K. 2006. Generic Routing Metric and Policies for WSNs. In: Proceedings of the European Workshop on Sensor Networks 2006, in print.

Shearer, P., 1999. Introduction to Seismology. Cambridge University Press, Cambridge, UK.

Stump, B.W., and Johnson, L.R. 1977. The Determination of Source Properties by the Linear Inversion of Seismograms. *Bulletin of Seismological Society of America*, 67(6), pp. 1489-1502.

Sustainable Bridges. 2006. "Sustainable Bridges – Assessment for Future Traffic Demands and Longer Lives." Integrated Project in the Sixth Framework Programme on Research, Technological Development and Demonstration of the European Union, FP6-PLT-001653, http://www.sustainablebridges.net.

To, A.C., and Glaser, S.D. 2005, Full Waveform Inversion of a 3-D Dislocation Inside an Artificial Rock, *Journal of Sound and Vibration*, 285(4-5), 835 - 857.