Smart Structures and Systems, Vol. 6, No. 3 (2010) 263-275

Wireless sensor networks for long-term structural health monitoring

Jonas Meyer*, Reinhard Bischoff, Glauco Feltrin and Masoud Motavalli

Empa, Swiss Federal Laboratories for Materials Testing and Research,
Ueberlandstrasse 129, 8600 Duebendorf, Switzerland

(Received May 1, 2008, Accepted July 1, 2009)

Abstract. In the last decade, wireless sensor networks have emerged as a promising technology that could accelerate progress in the field of structural monitoring. The main advantages of wireless sensor networks compared to conventional monitoring technologies are fast deployment, small interference with the surroundings, self-organization, flexibility and scalability. These features could enable mass application of monitoring systems, even on smaller structures. However, since wireless sensor network nodes are battery powered and data communication is the most energy consuming task, transferring all the acquired raw data through the network would dramatically limit system lifetime. Hence, data reduction has to be achieved at the node level in order to meet the system lifetime requirements of real life applications. The objective of this paper is to discuss some general aspects of data processing and management in monitoring systems based on wireless sensor networks, to present a prototype monitoring system for civil engineering structures, and to illustrate long-term field test results.

Keywords: wireless sensor networks; monitoring; cable-stayed bridge; energy management in sensor networks; data reduction.

1. Introduction

In the last decades, progress in electronics, computer science and sensor technology has allowed the development of robust and reliable structural health monitoring systems which meet the requirements of unattended long-term applications. This has intensified research on structural health monitoring (SHM) with the goal to improve the effectiveness of condition and performance assessment methods. Nevertheless, in daily civil engineering practice, the application of structural health monitoring is still a rarity. Deployments are mainly limited to very large structures or are performed for demonstration and research purposes. Important factors, which prevent a broad adoption of SHM systems, are system costs and data management. Both aspects are closely related to the logical structure of conventional monitoring systems.

In conventional SHM systems each deployed sensor is connected via long cables to a central data logger. The installation of such SHM systems is time consuming and expensive and the sensors are located far away from the data logger (Fig. 1). Furthermore, cabled systems have limited flexibility in terms of rearrangement of sensors and scalability. The installation costs become unimportant with respect to operation and maintenance costs only for new structures or for monitoring tasks that last for

---

*Corresponding Author, Research Engineer, E-mail: jonas.meyer@empa.ch

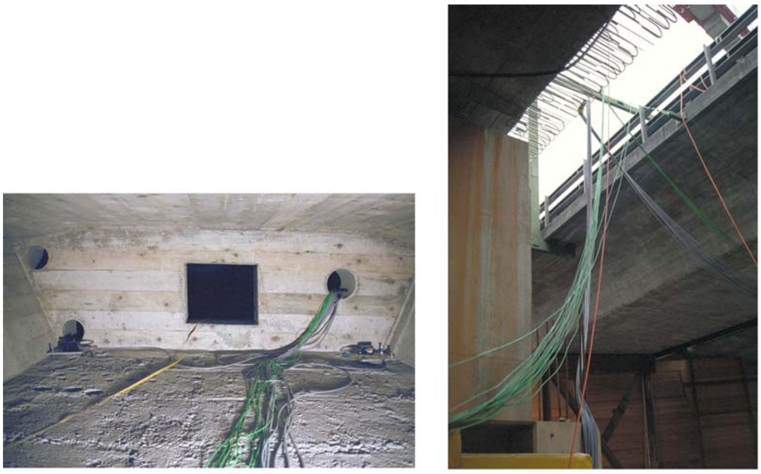

Fig. 1 Traditional wired SHM installation

many years. These cases, however, represent the minority of potential monitoring applications in civil engineering.

The adoption of wireless sensor networks (WSN)s for structural health monitoring promises to lower installation costs drastically. This is achieved by replacing the cables between the sensors and the data logger with wireless links. A WSN is basically a computer network consisting of many small, intercommunicating computers equipped with one or several sensors (Culler *et al.* 2004). Each small computer represents a node of the network and is commonly called a sensor node or mote. The hardware of a sensor node is built up of one or more sensors, a signal conditioning unit, an analog to digital conversion (ADC) module, a central processing unit (CPU) with memory, a radio transceiver and a power supply. Communication within the network is established using radio frequency transmission. One or several sensor nodes act as root nodes and represent the data sink in the network. A root node is connected to a base station that aggregates all data that is collected by the sensor nodes.

WSNs eliminate the cables connecting the sensors to the central logging unit and therefore solve the cable related problems of current conventional monitoring systems, making rapid and flexible deployments feasible. However, new WSN related challenges arise. In particular, the energy sources to power the wireless sensing devices are highly affected by the absence of cables. In fact, the nodes of the network have to be powered by independent sources like batteries that are severely limited in capacity. These limited energy resources are the most restricting factor in designing and implementing WSNs based monitoring systems for long-term applications, since the advantages of WSN over wired sensing systems come into play only if an unattended operation for a reasonably long period of time can be achieved.

So far, structural and infrastructure monitoring using WSNs has been demonstrated with short-term validation deployments in the field (Bennett *et al*. 2009, Kim *et al*. 2006, Mechitov *et al*. 2006, Lynch *et al*. 2006) or in the laboratory (see Nagayama *et al*. 2009 and Lu *et al*. 2008 for recent investigations). Combined strategies for prolonging system lifetime of WSNs were tested only marginally and their implications for hard- and software design were rarely discussed. This paper presents a monitoring system that is specifically designed for applications which target an overall system lifetime of several months to years and implements several methods for reducing energy consumption: ultra low power hardware components, multi-hop communication, low duty-cycle operation and data reduction. A long-term field deployment is presented that exploits all these energy saving methods.

2. Energy management in wireless sensor networks

The energy consumption aspect in WSN is of outstanding importance when addressing long-term monitoring applications. Because of the small capacity of batteries and the limited and unreliable recharging opportunities, energy consumption must be controlled very tightly. The main energy consumers are the radio, the sensors with associated signal conditioning and the microcontroller. Different approaches at the hard- and software level of a sensor node have been investigated to reduce energy consumption in WSN. Here we briefly discuss the most relevant techniques and their implications for structural monitoring applications.

Ultra low power hardware enables designing sensor nodes which operate from a battery for a reasonably long time. Today, ultra low power microcontrollers, which consume a few mW, are commercially available. The power consumption of radio chips is mostly dictated by the transmission range and varies between 50 and 100 mW, a figure that is significantly greater than the energy consumption of the microcontroller. The most energy efficient commercial WSN platforms that are available today have a power consumption that is smaller than 80 mW (Bischoff *et al.* 2006). However, this lower power consumption is obtained at the price of a low processing power and smaller memory size, which significantly affects the complexity of the tasks that can be performed on the sensor node.

Another means of reducing energy consumption is to operate the sensor nodes at a lower duty cycle. The duty cycle describes the fraction of time that a system is in an active mode with high power consumption. Energy is saved by operating the network in idle mode for a significant amount of time. In practice, only the radio, the sensors and the signal conditioning units are switched off, the CPU remains turned on. In low duty cycle operation mode, the lifetime of a system is predominately determined by the idle mode energy consumption of the node. Energy efficient commercial WSN platforms consume less than 10 mW in idle mode.

In terms of power consumption, wireless data transmission is much more expensive than data processing. In order to extend system lifetime, it is therefore inevitable to pre-process the raw sensor readings to reduce the data items that need to be transmitted to the base station. Transmitting all the raw data to the base station is only feasible when monitoring slowly varying physical parameters like temperature, humidity, static strain etc., since only a small amount of raw data is acquired. When monitoring vibration based processes, which produce large amounts of raw data, this strategy is hardly applicable without introducing huge batteries if a system lifetime of several months is targeted. Furthermore, since a significant amount of data has to be transferred to the base station, the rate of packet collisions increases so that a certain amount of data does not reach the base station. This data has either to be retransmitted, further increasing traffic and collisions, processor load and energy consumption, or it will be lost. To overcome this problem, different data processing strategies have been investigated:

- Data is encoded with data compression algorithms in a new representation that uses fewer bits than the original unencoded data. This data reduction is either lossless or lossy. A lossless data compression, which was tested on WSNs, is Huffman coding (Lynch *et al.* 2003). A compression algorithm with data loss was proposed by (Caffrey *et al.* 2004).
- The raw data is transformed into a new kind of information that requires less space in terms of bits. Examples of simple data transformation can be maxima, minima, mean values, rms of recorded

time series etc. Computationally more demanding transformations are the computation of natural frequencies or mode shapes of a structure (Lynch *et al*. 2006, Feltrin *et al*. 2006).

- Data evaluation on the sensor node level represents another means of reducing the amount of data transferred to the base station. It differs from the methods described above because the raw data is subjected to an evaluation. The sensor node software analyzes the data according to given criteria and decides if the data is relevant or not. Irrelevant data can already be discarded at the sensor node level. Data evaluation can be used to detect the occurrence of events that need to be monitored (e.g., crossing of a train on a bridge).

The limited energy resources restrict the complexity of the computation hardware on the sensor node. This restriction basically limits processing power, memory size and the achievable analysis complexity.

3. Monitoring system

3.1 Overall structure

In order to make monitored data remotely accessible, the WSN is connected to a remote control center. This overall monitoring system is composed of three subsystems, which are displayed schematically in Fig. 2.

The first subsystem is the WSN installed on the structure. Each sensor node acquires and processes the data and forwards it over the multi-hop network (data is passed on from node to node) to a root node. This root node forms the base station of the network where all data is collected and stored. The routing topology is periodically adapted by assessing the link quality between adjacent nodes and choosing the most reliable one for transmission. Due to this flexibility, it is possible to transfer data to the base station, even if some sensor nodes fail or do not operate correctly.

The second subsystem is the remote control center where all monitoring data is collected and written for long-term storage. Visualization and representation tools allow the end users to access the stored monitoring data and management tools enable remote observation, control and configuration of the WSN. All this functionality is integrated in Web applications. This enables interaction with the monitoring system over the Internet which gives infrastructure owners and operators better flexibility.

The third subsystem forms the communication link between the WSN deployed on the structure and the remote control center. This link, which is secure in terms of authentication and encryption, is established by the base station using standard wired or wireless communication technologies like Wireless LAN (WLAN) or Universal Mobile Telecommunications System (UMTS).

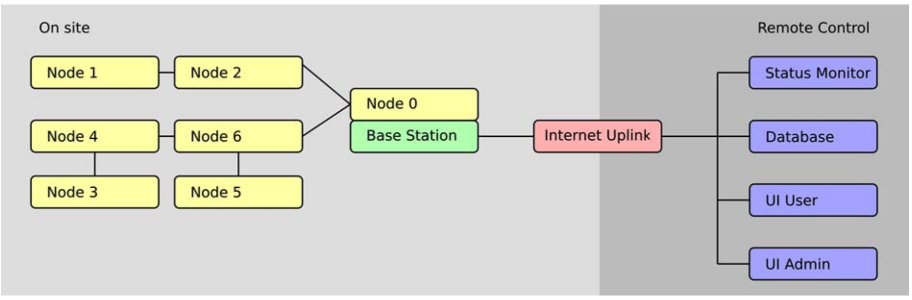

Fig. 2 Overview of the deployed health monitoring system showing the sensor network, the off site control and storage components and the link in between

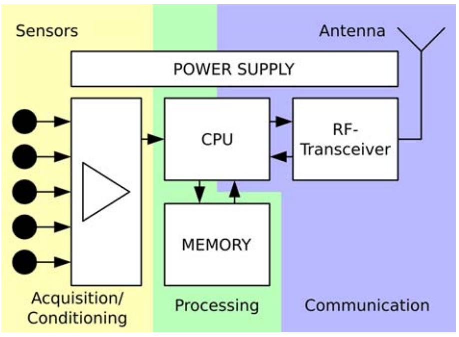

Fig. 3 Hardware structure of a sensor node

3.2 Hardware

The basic node hardware components are sensors, a signal conditioning unit, an analog to digital conversion (ADC) module, a central processing unit (CPU) with random access memory (RAM), a radio transceiver and a power supply (see Fig. 3).

3.2.1 Wireless sensor network platform

The present sensor nodes are based on the commercial Tmote Sky WSN platform (Polastre *et al*. 2005), which was chosen because of its low power consumption (5.4 mW in radio-off state and 65 mW in full operational mode). The main components of the Tmote Sky WSN platform are the ultra low power TI MSP430F1611 microcontroller, the FTDI FT232BM USB-interface which allows for programming the microcontroller over USB (Universal Serial Bus), and the Chipcon CC2420 low power radio chip. The 16-bit microcontroller features 10 kB of RAM and 48 kB of program memory (flash). It has 8 external 12 bit ADC ports of which 6 are accessible on a pin header. The ADC input ranges from 0 to 3.0 V. The maximum total sampling rate for all ports is 200 kHz at 12 bit resolution. The Chipcon CC2420 low power radio chip enables IEEE802.15.4 standard compliant wireless communication in the license free 2.4 GHz ISM (industrial, scientific and medical) frequency band. The radio chip is controlled by the microcontroller through the SPI port and a series of digital I/O lines, and offers power management capabilities to ensure low power consumption. The theoretically achievable maximum data throughput of the transceiver system is 250 kbps without framing and packet headers. In practice, however, the achievable maximum bandwidth is about 50 kbps.

3.2.2 Sensors and signal conditioning

The signal conditioning unit basically consists of amplification and filtering circuitry. It enables the interfacing of various sensing elements like strain gauges, capacitive and piezo-resistive accelerometers, LVDTs, etc. However, taking into consideration power consumption, it is reasonable to implement dedicated signal conditioning for each type of sensor instead of a general purpose conditioning unit.

Vibrations are measured with a LIS2L06 MEMS accelerometer from ST Microelectronics. It has been selected because of its high sensitivity of 0.6 V/g, its good noise performance of 0.2 mg at 50 Hz bandwidth, its low power consumption and low costs. It has an amplitude range of 2 g and a bandwidth of 0-2 kHz (capacitive accelerometer). The accelerometer is integrated into an electronic circuit containing a low pass filter with a cut-off frequency of 20 Hz and a low power signal amplifier. The power consumption

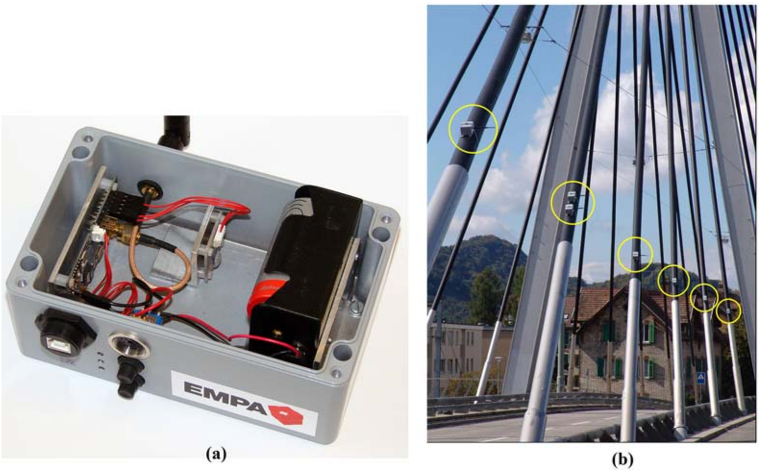

Fig. 4 (a) Rugged and waterproof 'nomotidaBox' for long-term outdoor deployments and (b) nomotida boxes mounted on the cable stays

of the accelerometer and signal conditioning is approximately 5 mW.

Ambient temperature and humidity are measured with the single chip sensor SHT11 from Sensirion. The sensor includes a capacitive polymer sensing element for measuring the relative humidity and a band gap temperature sensor. The maximum power consumption is reached during measurement and amounts up to 0.5 mW. The sensor is mounted in an opening of the housing and allows for temperature and humidity measurements outside of the enclosure.

3.2.3 Housing

Since the sensor nodes are deployed in harsh outdoor environments, the hardware components have to be protected against water, chemical, and mechanical impacts. The mote components, i.e., the sensors, the signal conditioning unit, the WSN platform and two 16500 mAh batteries are integrated into an aluminum enclosure (see Fig. 4). Switches and status LEDs are externally accessible. Furthermore, an external USB connector allows for reprogramming of the nodes without opening the enclosure. The housing is greater in size than required to provide space for additional sensors and signal conditioning boards. An external connector allows for connecting sensors which have to be mounted directly to the structure, i.e., strain gauges, corrosion sensors, etc.

3.3 Mote software

A WSN based monitoring system is a distributed sensing, computing and data storage system. A core component of the software system is that part running on the sensor nodes. Fig. 5 displays the logical structure of the node software architecture. Each node of the WSN provides the following functionality:

- Scheduling and execution of measurement tasks
- Processing and temporary storage of acquired data
- Management and configuration of data acquisition and processing (e.g., changing the sampling rate, reprogramming data processing algorithms)
- Self monitoring (e.g., supply voltage, communication link quality)

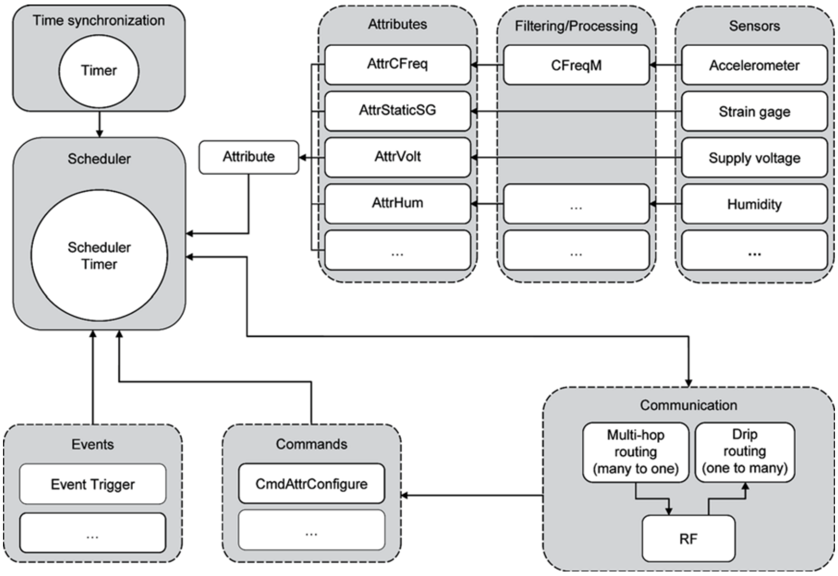

Fig. 5 Software architecture of a sensor node

- Reception and forwarding of data packets
- Coordination and management of communication and networking.

The software running on each mote establishes the wireless network, organizes the communication between the motes, acquires measurements, performs data processing and analysis, and generates alerts if particular conditions are met. Since every specific monitoring application differs from one another, flexible, open and scalable software architectures are desirable. The present monitoring application is implemented as TinyOS (Levis *et al.* 2005) components. TinyOS is a component-based software framework designed for sensor networks and tailored to fit the memory constraints of motes. It provides a concurrency model and mechanisms for structuring, naming and linking software components to form a robust network embedded system.

The basic network functionality is provided by low level network management components which operate independently from the actual monitoring application. They are responsible for establishing wireless links between adjacent nodes and building the routing tree as well as for network wide time synchronization and providing all nodes with a common time. From an application point of view it is not important how this is achieved. The application only has to have the possibility to send and receive data and to have access to global time information. The monitoring application is built on top of these modules. This allows for flexible exchange of communication and time synchronization components. A scheduler component forms the core of the actual monitoring application. It manages the measurement acquisitions performed by the mote. Its clock is synchronized to the global time. The scheduler configures the measurement and analysis parameters like sampling rate, filter coefficients, thresholds, etc., and triggers the data acquisition at the scheduled time.

The present prototype allows for the collection of information on the structural condition based on temperature, humidity and acceleration measurements. Moreover, it is possible to receive information on the internal state of each sensor node (battery voltage, routing) as well as communication parameters of the sensor network which describe the current condition of the monitoring system itself.

3.4 Uplink and off site components

The data items from the sensor network are collected at the base station. In order to make this data accessible for further analysis, the base station is connected to the internet via an UMTS uplink. The data is transmitted to an off site server and stored in a database (see Fig. 2). A Web interface to the database has been implemented which allows for flexible access to the stored data. The Web interface additionally allows for the configuration and management of the sensor network and the monitoring application. This functionality is not publicly accessible. The software architecture is discussed in more detail in (Bischoff *et al*. 2006).

4. Long-term force monitoring of cable stays

A potential application of WSN is cable tension force monitoring on stay cable bridges. Since each cable can be monitored independently, a completely distributed analysis algorithm can be adopted.

4.1 Background

Cable stay forces can be monitored by means of vibration measurements and natural frequency estimation. An appropriate cable model describes the relationship between the natural frequencies and the tensile cable force. The natural frequencies are usually determined by using frequency spectra or output only system identification algorithms. However, these methods are too expensive in terms of memory usage to be implemented on a mote. Parametric methods for spectral analysis allow for the estimation of natural frequencies with much less data than averaged spectrogram methods. Furthermore, natural frequencies can be estimated by computing the poles of the associated rational function model and are therefore not subjected to fixed frequency resolution issues.

In the present monitoring application, a simple autoregressive model has been used to estimate natural frequencies. Natural frequencies are computed using a very simple 2 parameter discrete time AR-model. The use of such a simple model is only possible if vibration components associated with a specific natural frequency can be isolated, which requires that the natural frequencies are well separated in the frequency spectrum. This is a requirement that cable stays usually fulfill quite well. The components can be isolated by first filtering the recorded data with a band pass filter. A detailed description of the implemented algorithm can be found in Feltrin *et al*. (2006).

4.2 Laboratory evaluation

Six cables of the test bridge at Empa (Gsell *et al.* 2004) have been equipped with accelerometers. The bridge deck was excited with an electro-magnetic shaker driven by a 1 to 80 Hz broad band, stochastic signal. Cable accelerations have been simultaneously recorded by the motes and a high precision data recorder. Subsequently, natural frequencies have been estimated during different deck loading states. The values computed on the motes fitted the results obtained with the data recorder and reached an accuracy of approximately 1% (for more details see Feltrin *et al*. (2006)).

4.3 Field deployment at the Stork Bridge in Winterthur

After successful laboratory experiments, a real life field deployment has been started on the Stork

Fig. 6 Stork Bridge in Winterthur, Switzerland

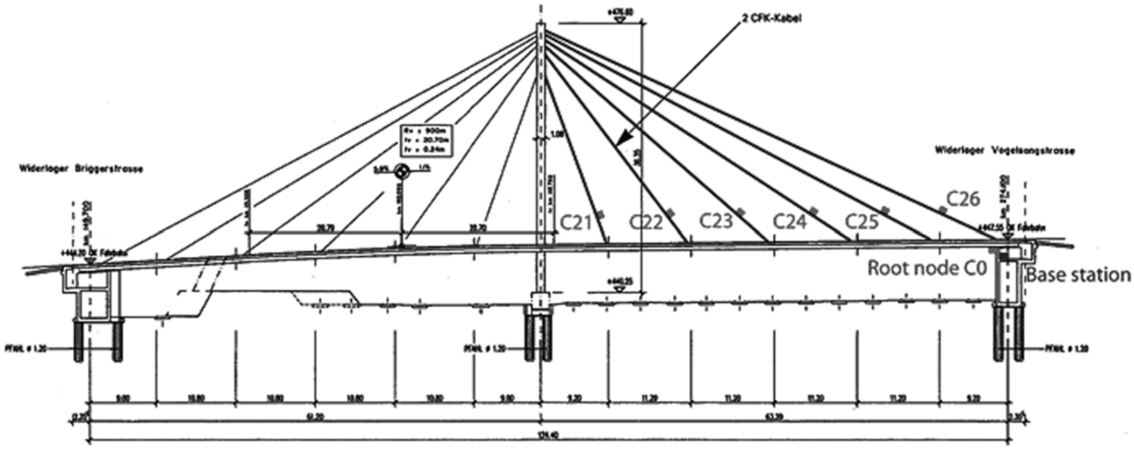

Fig. 7 Drawing of the Stork Bridge indicating the six instrumented cables. C21 - C26 are the positions where the motes are mounted to the cables

Bridge in Winterthur (Fig. 6). First, six of the 24 cable stays have been equipped with accelerometers wired to a high precision data recorder and the cable vibration excited by ambient vibration as well as the impulse response of the cables was recorded. This data was used for system identification and as a reference for the data acquired with the WSN. The WSN was deployed on the bridge in autumn 2006. Fig. 7 shows the node setup.

5. Results

Fig. 8 displays the natural frequencies of cables C24, C25 and C26 of the Stork Bridge during a period of 10 days. The natural frequencies were estimated from ambient vibration data sampled at 100 Hz using the algorithm described in (Feltrin *et al.* 2006). The typical RMS magnitude of the ambient vibration data was 10 to 30 mg, which is a very small value for the accelerometer and the 12 bit AD converter.

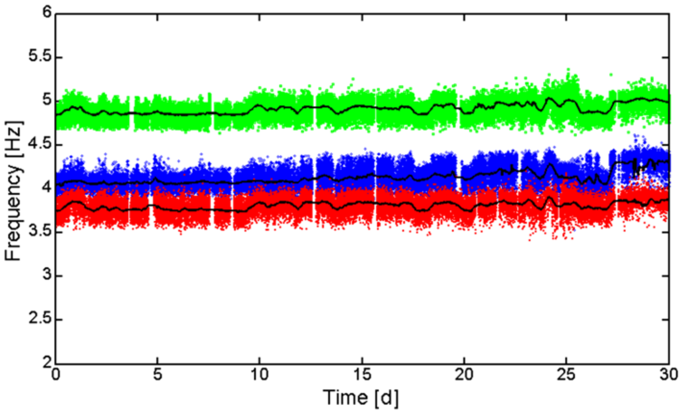

Fig. 8 Natural frequencies of three cables of the Stork Bridge

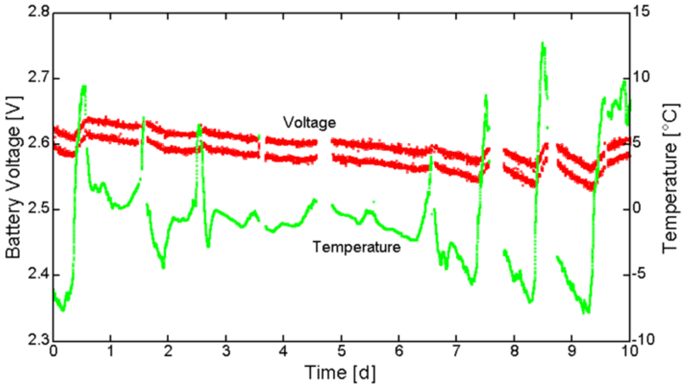

Fig. 9 Battery voltage and temperature measured on cable C26

The three bands displayed in Fig. 8 demonstrate that the algorithm generates estimations with a significant scattering. The accuracy of the frequency estimations is within 5-10%, which is a direct consequence of low levels of acceleration and the short data blocks used for estimating the natural frequency (blocks of 50 samples). Nevertheless, by using a moving average filter, relatively small variations of natural frequencies are still detectable (black curves inside the bands). This data processing step was done off site with data retrieved from the data base. For monitoring of cable tension, the accuracy is good enough, since only significant changes are of concern for ensuring structural safety of a bridge. In this place no statements about the cable stay condition are made, since the topic of this paper is to demonstrate the feasibility of monitoring systems based on WSN.

Fig. 9 shows the battery voltage and the temperature on mote C26 over a 10 day period. It clearly depicts the dependency of battery capacity on temperature. The voltage graph seems to consist of two lines. This is due to the fact that the battery voltage drops about 100 mV when the radio chip is turned on. Since the voltage measurement is not synchronized to this switching some measurements are taken when the radio is on and some when it is off. This results in the apparent double line voltage graph.

The graphs shown in Fig. 8 and Fig. 9 reveal data losses during some periods of time. The causes are stability issues in the communication software on the motes which lead to communication link break down and data loss at the base station. Bugs in the software can render the base station irresponsive and

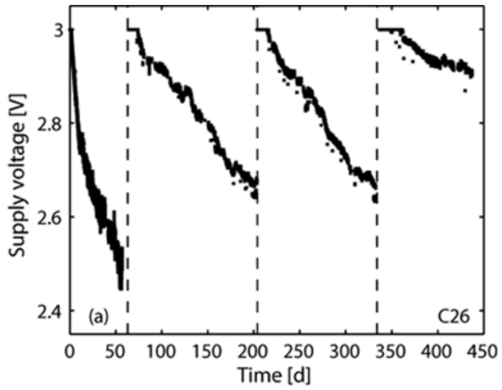

Fig. 10 Supply voltage of node C26, battery replacements are marked with vertical dashed lines

block the reception of the data packets from the motes. Data loss issues have to be investigated in more detail in order to fix the software bugs and make the monitoring system more reliable.

5.1 Energy consumption

Fig. 10 shows the battery voltage of the sensor node C26 over a period of 450 days starting from January 16th, 2007. New batteries were installed the day before. Three battery replacements were performed during this period: March 20th (day 63), August 6th (day 203) and December 14th (day 333). In the first period the network was operated with a duty cycle of 40% (40% of the time the radio is on) and the estimation of natural frequencies occurred every minute. During this period, the voltage dropped by approximately 0.5 V. Since a node operates correctly if the battery voltage is greater than 2.5 V, its lifetime was approximately 60 days.

After the first battery replacement on day 63 a new version of the sensor node software was installed that operated the network with a duty cycle of 10%. The estimation of natural frequencies occurred every 2 minutes. With this configuration the node lifetime reached approximately 180 days. After the second battery replacement, the duty cycle was reduced to 7%. The frequency of natural frequency estimations remained unchanged. This small reduction of duty-cycle did not influence the lifetime of the node, which was also approximately 180 days.

These measurements demonstrate that the node lifetime is not proportional to the duty-cycle. As mentioned above only the radio is switched on and off and therefore its energy consumption is proportional to the duty-cycle. The other components, i.e., the microcontroller, sensors, and signal conditioning boards are permanently turned on and thus, their energy consumption is constant. If the duty-cycle is high, the overall energy consumption is predominantly affected by the radio and the consumption of the other components is insignificant. If the duty-cycle is low, the consumption of the radio becomes negligible and the remaining components dominate the overall energy consumption and pose an upper limit on the system lifetime.

The last sensor node software version, which was operating after the third battery replacement (day 200), switched the sensor off after completing the measurement. The duty cycle was further reduced to 2% and the period of natural frequency estimations was set to 5 minutes. A lifetime estimation based on the voltage plots predicts a node lifetime of at least 450 days and therefore far beyond one year.

6. Conclusions

The presented monitoring system has been successfully implemented and tested on the Stork Bridge in Winterthur. The deployment shows that cable stay force monitoring based on wireless sensor networks is feasible and that appropriate algorithms and strategies can be implemented which fit the limited memory and computation resources of the motes. The natural frequencies computed on the nodes reached an accuracy of about 5-10% compared to the results obtained with a high precision data logger. The feasibility is based on four strategies for reducing the energy consumption: ultra low power hardware components, multi-hop communication, low duty-cycle operation and data reduction. The latter method which reduces transmitted data by decentralized processing is a key aspect for enabling long sensor node lifetime. Various software tools have been developed which allow the monitoring system operator to access the gathered data and configure the network and monitoring tasks remotely.

In the next period the wireless sensor network prototype will be further improved and optimized. During the test some issues concerning the stability of the mote software arose which have to be addressed in order to provide reliable monitoring. Additionally the power consumption has to be further reduced to enable long-term deployments.

Acknowledgements

Part of this work was performed within the Project "Sustainable Bridges: Assessment for Future Traffic Demands and Longer Lives" of the 6th Framework Program of the European Commission. The authors acknowledge the Swiss State Secretariat for Education and Research for its financial support.

References

Bennett, V., Abdoun, T., Shantz, T., Jang, D. and Thevanayagam, S. (2009), "Design and characterization of a compact array of MEMS accelerometers for geotechnical instrumentation", *Smart Struct. Syst.,* **5**(6), 663-679.

Bischoff, R., Meyer, J., Feltrin, G. and Saukh, O. (2006), "Monitoring of civil infrastructures using wireless sensor networks", *Proceedings of the APWSHM'06 1st Asia-Pacific Workshop on Structural Health Monitoring*, Yokohama, December.

Caffrey, J., Govindan, R., Johnson, E., Krishnamachari, B., Masri, S., Sukhatme, G., Chintalapudi, K., Dantu, K., Rangwala, S., Sridhara, A., Xu, N. and Zuniga, M. (2004), "Networked sensing for structural health monitoring", *Proceedings of the 4th International Workshop on Structural Control*, Ed. R. Betti, Columbia University, New York.

Culler, D., Estrin, D. and Srivastava, M. (2004), "Overview of sensor networks", *IEEE Comput.,* **37**(8), 41-49.

Feltrin, G., Meyer, J., Bischoff, R. and Saukh, O. (2006), "A wireless sensor network for force monitoring of cable stays", *Proceedings of the 3rd International Conference on Bridge Maintenance, Safety and Management, IABMAS 06*, Porto, July.

Gsell, D. and Motavalli, M. (2004), "Indoor cable-stayed GFRP bridge at EMPA, Switzerland", *Proceedings of the 4th International Conference on Advanced Composite Materials in Bridges and Structures,* Calgary.

Kim, S., Pakzad, S., Culler, D.E., Demmel, D., Fenves, D., Glaser, S. and Turon, M. (2006), *Health monitoring of civil infrastructures using wireless sensor networks*, Technical report No. UCB/EECS-2006-121, University of California, Berkeley, CA.

Levis, P., Madden, S., Polastre, J., Szewczyk, R., Whitehouse, K., Woo, A., Gay, D., Hill, J., Welsh, M., Brewer, E. and Culler, D. (2005), *Tiny OS: An operating system for wireless sensor networks, Ambient Intelligence*, Springer-Verlag, New York.

Lu, K.C., Loh, C.H., Yang, Y.S., Lynch, J.P. and Law, K.H. (2008), "Real-time structural damage detection using wireless sensing and monitoring system", *Smart Struct. Syst.,* **4**(6), 759-777.

Lynch, J.P., Yang, W., Loh, K.J., Yi, J.H. and Yun, C.B. (2006), "Performance monitoring of the Geumdang bridge using a dense network of high-resolution wireless sensors", *Smart Mater. Struct.,* **15**(6), 1561-1575.

Lynch, J.P., Sundararajan, A., Law, K.H., Kiremidjian, A.S. and Carryer, E., (2003), "Powerefficient data management for a wireless structural monitoring system", *Proceedings of the 4th International Workshop on Structural Health Monitoring*, Ed. Chang, F.K., Stanford University, Stanford, CA.

Mechitov, K., Kim, W., Agha, G. and Nagayama, T. (2006), "High-frequency distributed sensing for structure monitoring", *Transac. Soc. Instr. Control Eng. (SICE)*, **E-S-1**(1), 109-114.

Nagayama, T., Spencer, Jr., B.F., Mechitov, K.A. and Agha, G.A. (2009), "Middleware services for structural health monitoring using smart sensors", *Smart Struct. Syst.,* **5**(2), 119-137.

Polastre, J., Szewczyk, R. and Culler, D. (2005), *Telos: Enabling ultra-low power research*, Information Processing in Sensor Networks/SPOTS, Berkeley, April.

Sazonov, E., Janoyan, K. and Jha, R. (2004), "Wireless intelligent sensor network for autonomous structural health monitoring", *Proceedings of SPIE's Annual International Symposium on Smart Structures and Materials,* San Diego, CA.