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A LOW-POWER WIRELESS SENSOR NETWORK FOR STRUCTURAL HEALTH MONITORING

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Abstract

The objective of this paper is to present a prototype wireless sensor network for monitoring of civil engineering structures. The network consists of several remote sensor nodes distributed over a structure, representing the data sources and a base station (data logging and configuration unit), representing the data sink in the network. Each node is equipped with several sensors, a data acquisition and signal processing unit and a radio transceiver. The acquired data is pre-processed on the sensor node before it is sent to the base station. The aggregated data can be remotely accessed over the Internet. Software tools permit to administrate the network and re-schedule measurement tasks remotely. The acquired data is stored in a relational database that can be accessed and updated by different data query and visualization tools. After preliminary laboratory experiments a sensor network has been deployed on a cable stayed road bridge to evaluate the performance of the system. The deployed system monitors the tension force of the stays as well as temperature and humidity. The force is monitored by tracking natural frequencies estimated from measured ambient cable vibrations.

INTRODUCTION

Basically every structural health monitoring (SHM) system is made up of various sensors measuring specific physical parameters, a data acquisition unit and a storage device to save the acquired data. Traditional SHM systems show a star like topology where each deployed sensor is connected via long cable runs to a central computer acting as data acquisition and storage device. The installation of such systems tends to be time consuming and therefore expensive (Figure 1). Especially in the field of civil engineering where the structures are typically large, the sensors can be located long way away from the data acquisition unit resulting in high installation costs. The installation costs have shown to be a major issue preventing a broad application of monitoring techniques to large scale infrastructure. Furthermore, the long cable runs are prone to pick up noise reducing the effective accuracy of the acquired data and claiming for expensive high quality cables. Moreover, these cables are susceptible to mechanical damage involving considerable maintenance effort. Cabled systems also tend to offer a limited flexibility in terms of rearrangement of sensors and scalability. The adoption of wireless sensor networks (WSN) techniques to SHM applications promises to overcome these drawbacks.

Although the elimination of the cables connecting the sensors to the central logging unit solves the cable related problems mentioned above, new WSN related challenges arise. Particularly the resources to power the wireless sensing devices (motes) are highly affected by the absence of cables. In fact, the motes have to be powered by auto-

nomous sources like batteries or solar cells which are severely limited in capacity. The limited energy resources on each mote present the most restricting factor in designing and implementing WSN based monitoring systems. Therefore, novel monitoring and measurement as well as communication strategies taking into account the limited energy resources have to be developed and tested.

In terms of power consumption, wireless data transmission is much more expensive than data processing. In order to extend system lifetime it is preferable to preprocess the raw sensor readings to reduce the data items needed to be transmitted to the base station. Many recent WSN based SHM systems transmit the raw data streams to the base station and analyze them in the traditional centralized way [1,2]. Without introducing huge batteries, this is not a viable solution if a system lifetime of several months to years is targeted. For long term monitoring applications distributed analysis algorithms have to be introduced which allow for decentralized data reduction or even condition assessment. At best the condition of a structure could be assessed in a completely decentralized way and only a few condition statements would have to be sent to the base station.

However, this is by far not possible for every analysis method. The limited energy resources additionally restrict the complexity of the applicable computational hardware on the mote. These restrictions basically limit memory size and computation speed and highly affect the achievable analysis complexity.

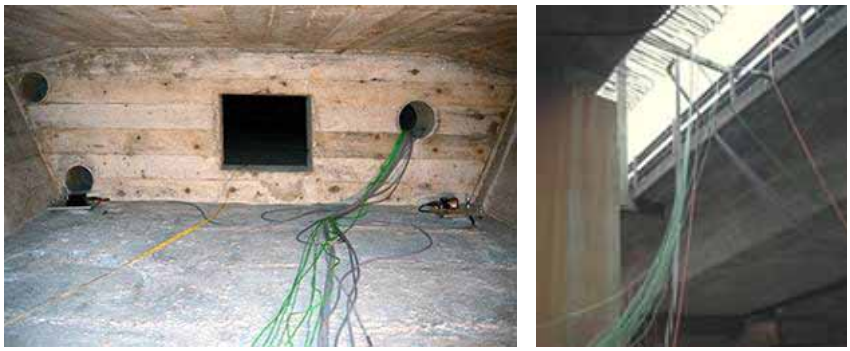

Figure 1. Traditional wired SHM installations.

FORCE MONITORING OF CABLE STAYS

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

Background

Cable stay force can be monitored by means of vibration measurements and natural frequency estimation. An appropriate cable model describes the relation 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. In the present monitoring application, a simple autoregressive model which requires significantly less memory has been used to estimate the natural frequencies of the cable stays.

Natural Frequencies Estimation Algorithm

Parametric methods of spectral analysis allow estimating natural frequencies with much less data than averaged spectrogram methods. Furthermore, the 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. The 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 the vibration components associated with a 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 [3].

Laboratory Evaluation
Six cable stays of the laboratory bridge at Empa [4] have been instrumented with accelerometers. The bridge deck was excited with an electro-magnetic shaker driven by a broad band, stochastic signal ranging from 1 to 80 Hz. The cable accelerations have been simultaneously recorded with the motes and with a high precision data recorder. Subsequently the natural frequencies have been estimated during different deck loading states. The values computed on the motes fitted reasonably well with the results obtained using the data recorded with the high precision data acquisition device and reached an accuracy of approximately 1% errors (for more details see [3]).

STORK BRIDGE DEPLOYMENT

Figure 2. Stork Bridge in Winterthur, Switzerland.

After successful completion of the laboratory experiments, a real life field deployment has been started. The Stork Bridge (Figure 2) in Winterthur was chosen as investigation object. In a first phase, six of the 24 cable stays have been instrumented 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 obtained with the WSN. In a second phase, started in autumn 2006, the WSN has been deployed on the bridge. Figure 3 shows the setup.

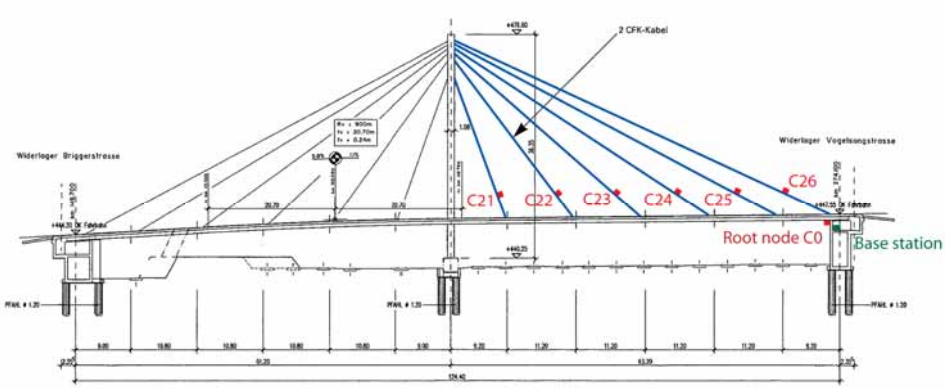

Figure 3. Elevation of the Stork Bridge indicating the six instrumented cables. C21 - C26 are the positions where the motes are mounted to the cables.

The 'nomotidaBox'

Since a deployment over several months including the winter season was planned, a rugged and waterproof enclosure is essential. Due to its high stability, an aluminum box was chosen. Figure 4 shows an open 'nomotidaBox'. The enclosure contains sensors, a signal conditioning unit, the Telos WSN platform [5] and a power supply. The switches and LEDs of the Telos hardware are externally accessible. An external connector allows for connection of sensors which have to be mounted directly to the structure, i.e. strain gages, corrosion sensors etc.

Figure 4. Rugged and waterproof 'nomotidaBox' for long-term outdoor deployments. Nomotida boxes mounted on the cable stays.

Sensors and Signal Conditioning

Most WSN hardware platforms feature by default temperature and humidity sensing capabilities or at least offer an interface to connect dedicated sensors. The Telos platform exhibits an interface for a Sensirion humidity sensor. A SHT11 is mounted into an opening in the enclosure and allows for temperature and humidity measurements outside of the box.

The vibration measurements needed for the stay cable tension force monitoring are acquired with a MEMS accelerometer. A 2-axis sensor is used in order to allow for in plane and out of plane vibration measurements. A variety of MEMS accelerometers exist on the market with a wide range of performance characteristics and prices [6]. The

LSI2L06 accelerometer from ST Microelectronics has been chosen because of its good noise performance of 0.2mg at 50Hz bandwidth, low power consumption and low costs.

The signal conditioning unit basically consists of amplification and filtering circuitry. It enables to interface various sensing elements like strain gages, capacitive and piezo-resistive accelerometers, LVDTs etc. However, considering power consumption, it is reasonable to implement dedicated signal conditioning for each type of sensor instead of a general purpose conditioning unit. Therefore a very simple conditioning circuit has been implemented for this deployment.

Mote Software

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 each other, flexible, open and scalable software architectures are desirable. The present monitoring application is implemented as TinyOS [7] components. TinyOS is a component-based software framework designed for sensor networks and tailored to fit the memory constraints of the 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.
- Network wide time synchronization to provide all nodes with a common time base.

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 the 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 rates, filter coefficients, thresholds etc. and triggers the data acquisition at the scheduled time.

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

The energy constraints mentioned above also apply to the software components. Therefore, all modules are implemented using energy-aware approaches in order to maximize the lifetime of the monitoring system.

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. **FIGURE 5** shows the diagram of the system wide setup. A Web interface to the database has been implemented which allows for flexible access to the stored data. The Web interface additionally allows for 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 [8]

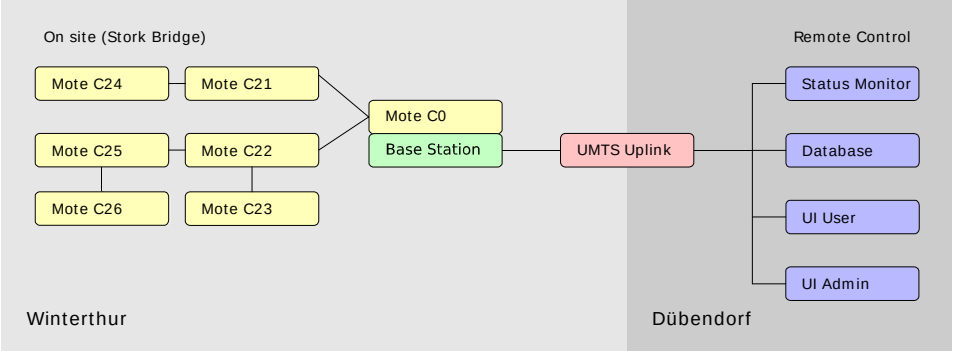

Figure 5. Overview of the deployed health monitoring system showing the sensor network, the off site control and storage components and the link in between.

RESULTS

Figure 6 displays the natural frequencies of the 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 100Hz using the algorithm described in [3]. 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 integrated into the motes. The three bands displayed in Figure 6 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 level of accelerations and the short data blocks used for estimating the natural frequency (blocks of 50 samples). Nevertheless, by using a moving average filter, relative small variations of natural frequencies are still detectable (black curves inside the bands). This data processing step was done at the off site control center 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.

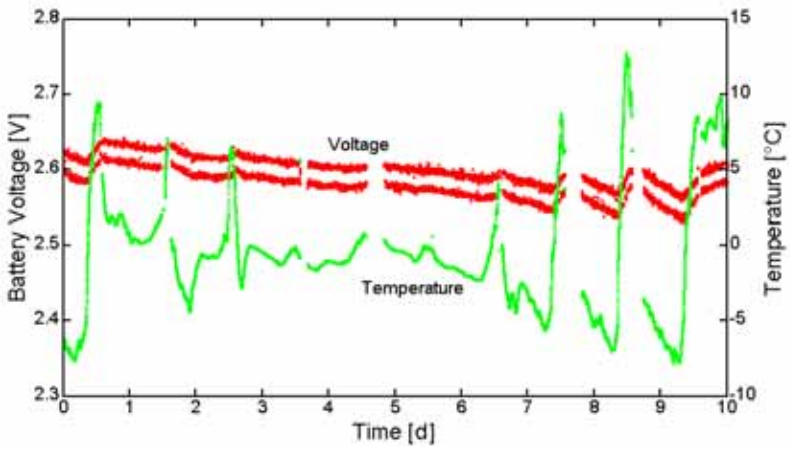

FIGURE 7 shows the battery voltage and the temperature on mote C26 over a 10 day period. It clearly depicts the dependency of battery capacity on temperature. The voltage graph seems to consist of two lines. This is due to the fact that the battery voltage drops about 100mV when the radio chip is turned 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 FIGURE 6 AND

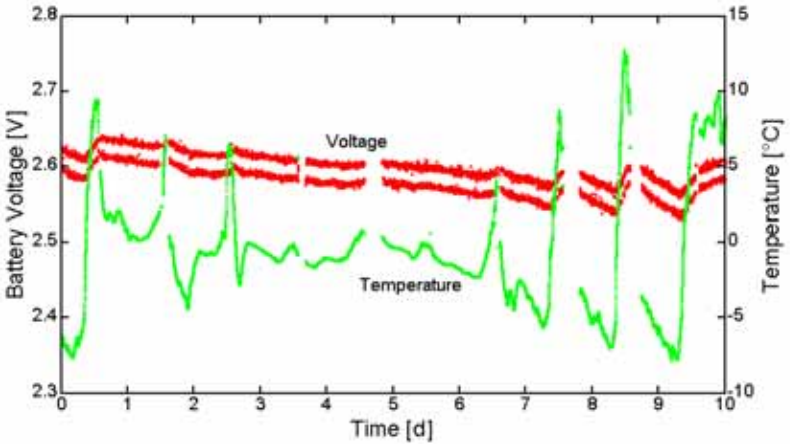

FIGURE 7 reveal data losses during some periods of time. The causes of these losses are on the one hand stability issues in the communication software on the motes which lead to communication link break down. On the other hand data from the motes is lost at the base station. Bugs in the software can render the base station irresponsive and block the reception of the data packets from the motes.

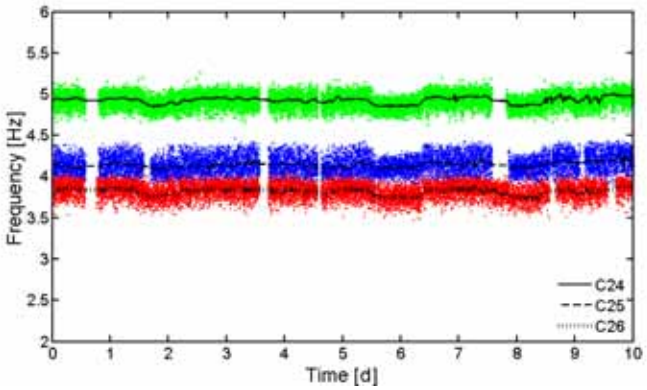

Figure 6. Natural frequencies of three cables of the Stork Bridge.

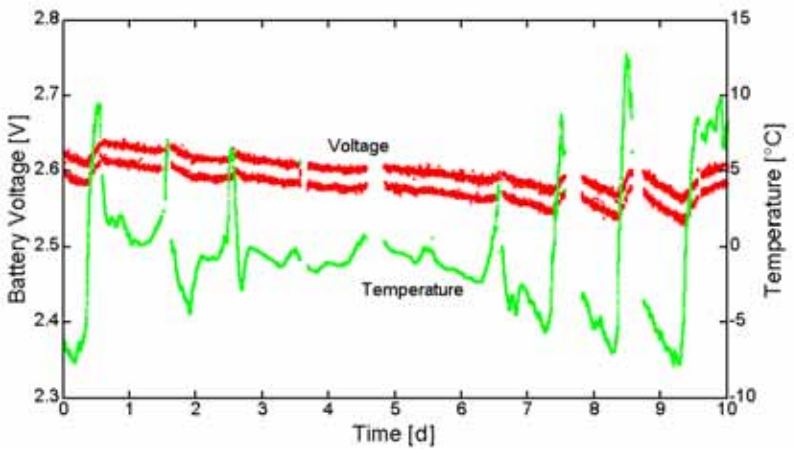

Figure 7. Battery voltage and temperature measured on cable c26.

CONCLUSIONS AND FURTHER WORK

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 and provide reasonably accurate results. Various software tools have been developed which allow the monitoring system operator to access the aggregated data and configure the network and monitoring tasks in a suitable way.

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 solved in order to provide reliable monitoring. Additionally the power consumption has to bee further reduced to enable long term deployments.

ACKNOWLEDGEMENTS

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