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Modular Wireless Sensor Network for Long-Term Structural Health Monitoring

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ABSTRACT: This paper presents a prototype of a low-power wireless sensor network platform for medium- to long-term structural health monitoring deployments. The platform features modular design of network nodes where sensor conditioning, data processing unit and wireless communication module each forms a separate subsystem. The separation of data processing and communication tasks into individual hardware modules results in simpler management of resources and more computing and memory resources for data processing. The capabilities of the monitoring system are demonstrated on a real world setup on a cable-stayed bridge. The goal was to monitor the tension force of cable-stays via natural frequency estimation based on frequency spectra. The investigation shows that the on-the-fly information extraction by in-mote data processing can be performed with nearly negligible power consumption. This allows, depending on the measurement interval, to reach system lifetimes of years.

1 INTRODUCTION

The potential of wireless sensor networks for short term structural monitoring were demonstrated in several investigations (Glaser, 2004, Lynch et al., 2006, Kim et al., 2006, Gangone et al., 2008). These deployments address only marginally strategies for prolonging the lifetime of a WSN and their implications on the hardware and software design. The issues related to medium and long term monitoring were investigated within the EC project "Sustainable Bridges" (Olofsson et al., 2005, Feltrin et al., 2007). This monitoring system was specifically designed for applications with high data processing work load and targeted an overall system lifetime of several months to a year. The results from field deployment demonstrate that the integration of several tasks like data acquisition, data processing, data communication, time synchronization, duty cycle, task scheduling etc. into one software system running on a single low power microcontroller generated a very sensitive system in terms of reliability and robustness.

2 SYSTEM DESIGN

To overcome the drawback mentioned above, a modular hardware design was investigated where sensing, data processing and wireless communication modules form separate subsystems. Such a modular design reduces the interaction between data acquisition, data processing and network functionality, and thus enables an easier adjustment of software to various monitoring needs.

An overview of the modular hardware architecture of a wireless node with the basic sensing, processing and communication subsystems is presented in Figure 1. The sensing subsystem is a

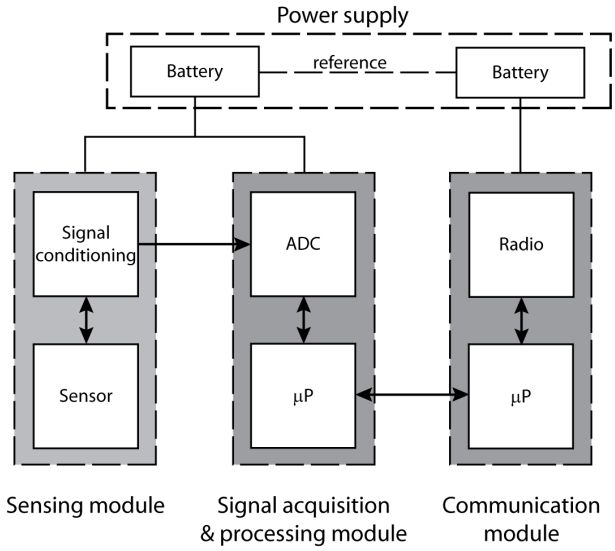

Figure 1: Modular hardware design of WSN mote consisting of communication, processing and sensing subsystems.

module with a dedicated sensor and analogue signal conditioning circuit. The processing module performs the analogue to digital conversion and data processing and the communication module provides the wireless networking functionality.

2.1 Sensing module

The vibrations are captured with the LIS3L02 capacitive MEMS acceleration sensor of ST Microelectronics that can be operated with a power supply of 3 V and has a power consumption of 4 mW. The signal conditioning unit basically consists of an analogue amplification and filtering circuit (Figure 2a). Both circuits are realized using a low-power amplifier. The filtering circuitry consists of a 1st-order high-pass and two 2nd-order low-pass Butterworth filters. The high-pass filter was implemented to increase the amplification range of the AC acceleration signal by removing the DC sensor signal component due to gravitation. The low-pass filter is used as anti-aliasing filter with a cut-off frequency of 20 Hz. The signal amplification factor has been set according to the measured signal dynamics to 50 times. By this factor, the amplitude range of the signal is limited ±50 mg.

2.2 Signal Acquisition and data processing module

The requirements for the signal acquisition and data processing unit are a low power A/D converter with a suitable resolution and a central processing unit with enough memory to store the software modules for task management, data acquisition, data processing, and data communication. The MSP430F1611 microcontroller of Texas Instruments was considered as a suitable solution. It features 10 kB RAM, 48 kB Flash, an 8 channel A/D converter with 12 bit resolution and very low power consumption.

2.3 Communication module

The wireless communication module is implemented with the WiseNode platform. WiseMAC, a low power wireless and dedicated medium access protocol and a tree routing protocol are implemented on the WiseNode's microcontroller (see Figure 2b). The WiseMAC protocol is providing a very energy efficient radio communication by coordinating the medium usage,

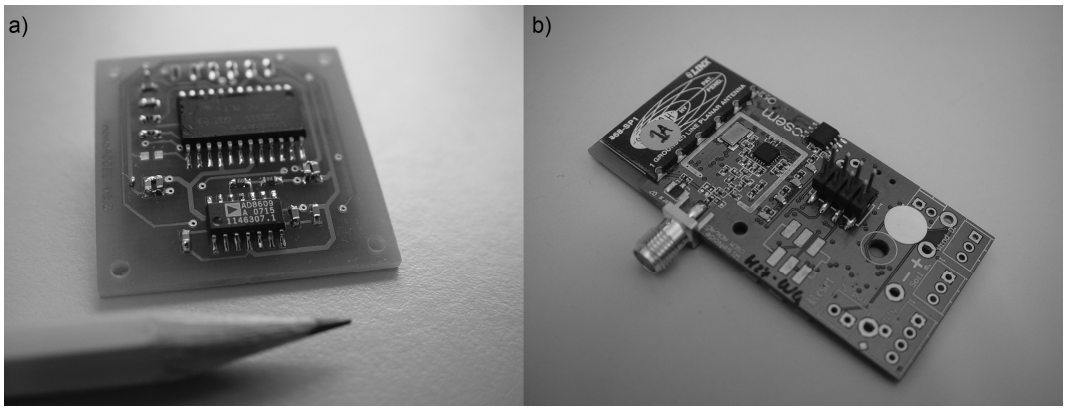

Figure 2: a) MEMS accelerometer sensing module with analog signal conditioning circuitry. b) WiseNode V4 wireless communication module.

locally synchronizing communication activities (duty cycle) of the neighboring nodes, reducing the energy loss due to the packet collisions, idle listening and packet overhearing (El-Hoiydi and Decotignie, 2004). The latest version of the WiseNode platform is based on the MSP430F1611 microcontroller, and on a board radio and antenna that operate at 868/915 MHz. The node also runs a clock synchronization algorithm to give a common acquisition reference to all nodes. The network self organizes from the root node.

2.4 Software system

The signal acquisition and data processing module and the wireless communication module run their own application software and are communicating over an UART interface. The central part of the signal acquisition and data processing module software is the scheduler module that performs the scheduling of the measurement tasks. The scheduler module uses the sensor module to initiate the measurements by setting-up the configuration parameters of the sensors. The sensor module is also responsible for controlling the analogue to digital conversion to acquire the conditioned sensor signal from the sensing module.

After completion of the signal acquisition, the measured raw data is forwarded to the data processing module, which extracts the desired information. Finally, the results of data processing are passed back to the scheduler module which transmits the data packet with the processing results to the communication module. This module wirelessly communicates it over the multi-hop WiseNET to the network sink.

After the measurement and the data processing are completed and the results have been sent to the communication module, the scheduler sets an internal alarm timer to wake-up the sensing and data processing module for the next measurement and processing cycle and puts the module into a power-saving sleep mode.

3 DATA PROCESSING

3.1 Cable stays tension monitoring

Cable tension monitoring is often performed by correlating the measured natural frequencies with those predicted with a cable model. First investigations of vibration-based cable tension evaluation were based on simple taut string theory (Casas, 1994). More advanced identification methods include the effect of bending stiffness by simple approximation formulas of the natural

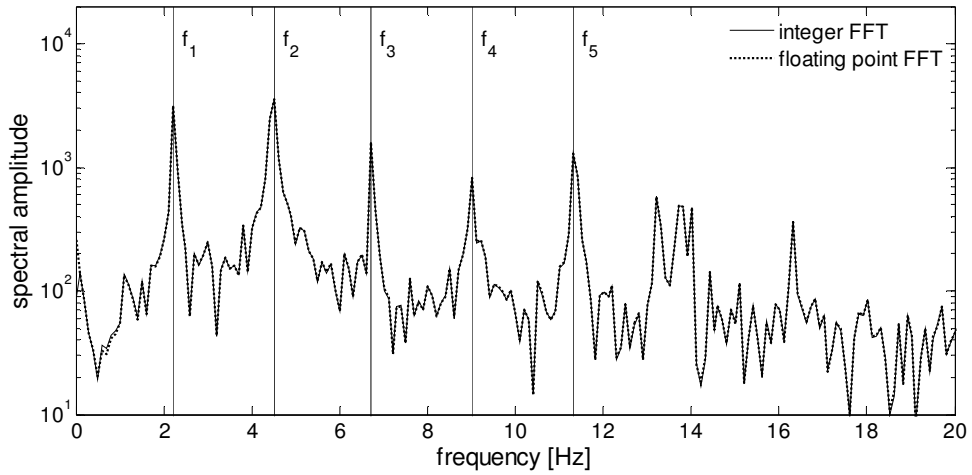

Figure 3: The spectral amplitude of the integer approximation of FFT compared to the spectral amplitude of the standard floating point FFT. A real acceleration signal from a bridge cable has been taken as input for this analysis.

frequencies (Ladret et al., 2002). A more refined method that does not rely on simple approximation formulas is presented in Feltrin et al., 2006.

The natural frequencies are the key information needed to estimate the cable tension. Hence, they present the only data that needs to be transmitted to the network sink, while the rest of raw data (time series of accelerations) can be discarded. From the initial amount of data, e.g. 1024 samples, the relevant information that will be communicated are reduced to several natural frequencies. This approach results in a drastic reduction of data that has to be wirelessly communicated, which significantly reduces the power consumption of the system and prolongs the network lifetime.

3.2 Computation of natural frequencies

The first step is to perform a Fast Fourier Transform (FFT) algorithm on the acquired vibration data and compute the frequency spectrum. The second step is to identify spectral peaks that correspond to the cable natural frequencies by using a peak detection algorithm. After the peaks have been identified, a small set of potential natural frequencies are selected and communicated to the network sink within a single data packet.

The envisaged methodology presents, however, a challenge to implement on the small computing resources of the microcontroller system. The first challenge arises from the limited RAM memory resource which totals 10kB for the whole software application. Since the measured signal takes 2kB of memory for a time series of 1024 16 bit samples, the requirement is that as little as possible additional memory needs to be used for intermediate data storage during the data processing. This means that the whole data processing should take place in the same memory so that the temporary results of all intermediate processing stages and the final results are stored in the same memory, overwriting the data from the previous stage. Fortunately, the FFT algorithm, which represents the most demanding data processing step, can be implemented to fulfill this requirement.

The second challenge concerns the microcontroller central processing unit (CPU) that operates on the internal 4MHz clock, which is very slow when compared to modern processor speeds in the gigahertz range. Usually, the FFT algorithm is performed in floating point arithmetic. However, since the MSP430F1611 microcontroller does not support hardware floating point

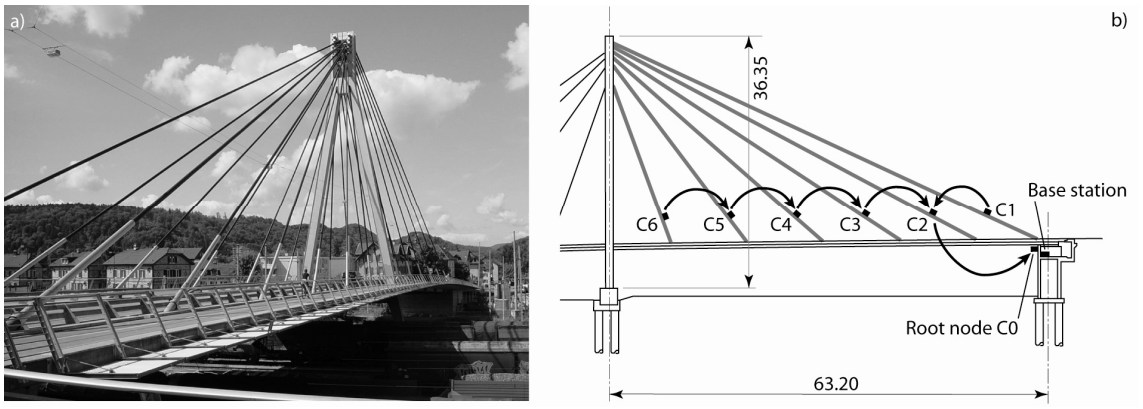

Figure 4: a) Stork Bridge in Winterthur, Switzerland. b) Topology of the multi-hop network.

operations, all floating point operations have to be emulated in software with integer operations. This overhead results in a greater code size and longer execution time. Since the digitized signal is stored as 16bit integer values, it is reasonable to perform the data analysis by using just integer operations instead of floating point operations. This approach results in a smaller memory footprint (both RAM and ROM) and significantly reduces the execution time. As a consequence, the power consumption required for the data processing is also reduced, thus increasing the lifetime of a node.

An integer-only implementation of the FFT is trivial to achieve with the simple arithmetic operations of adding and subtracting, but the problem is the multiplication operation. One way to achieve an efficient integer multiplication is to roughly approximate the floating point multiplication by using a single integer operation. Two 16-bit integer operands are multiplied to get a 32-bit result, but then only the higher 16 bits are taken as the final result, i.e. the lower 16 bits of the result are discarded.

Evidently, such an approximation mechanism may introduce a significant error when compared to the standard floating point FFT implementation. By scaling the recorded time series with a suitable factor greater equal to one, however, the approximation error can be maintained within an acceptable range. Figure 3 compares the frequency spectrum computed with a 16 bit integer approximation FFT with the spectrum obtained by the standard 32 bit floating point FFT. As can be observed, the result of the integer approximation FFT matches very well with the floating point FFT.

4 FIELD TESTS

4.1 Field Deployment

The developed WSN has been deployed outdoors to study the performance of the system in real life conditions. It has been installed on a cable-stayed bridge in Winterthur (see Figure 4a). The six node network (C1 to C6) and a sink node (C0) are installed on adjacent stay-cables of the Stork Bridge. Figure 4b) illustrates the default multi-hop communication topology used to send and forward the data packets to the sink node, which is located under the bridge deck and is attached to a base station powered from the mains power supply. The base station establishes a communication link with a computer in Empa's laboratory over the cell phone network using standard Internet communication protocols. More information on these parts of the monitoring system can be found in Feltrin et al., 2007.

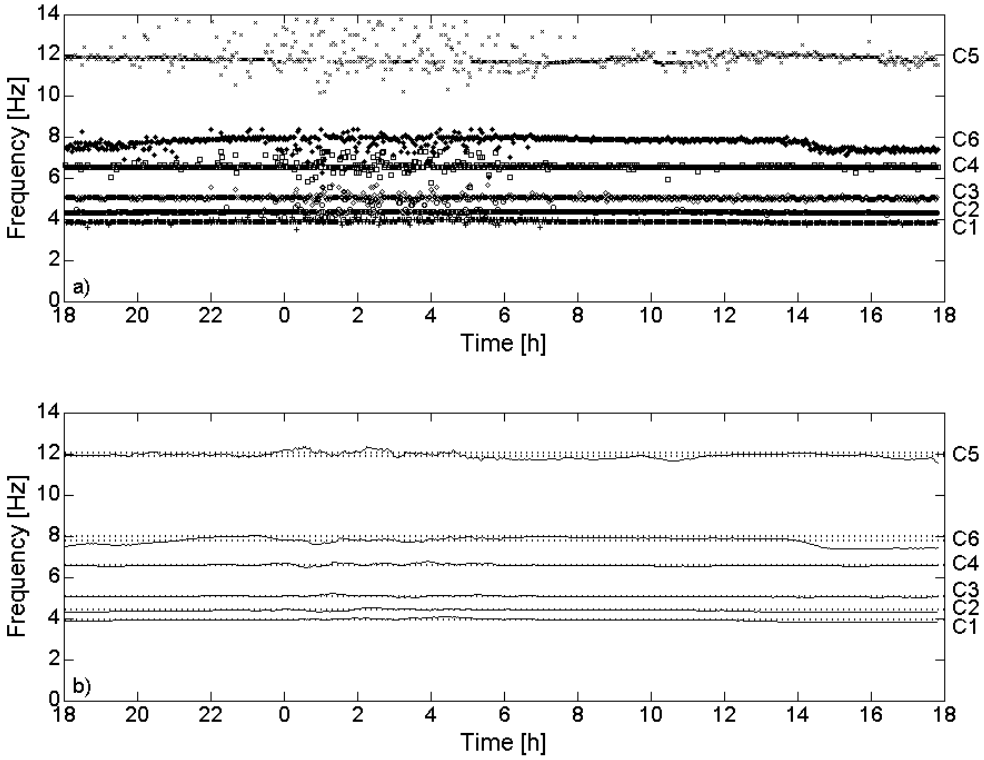

Figure 5: a) Natural frequencies of monitored stay-cables. b) Natural frequencies smoothed with a moving average filter.

In order to protect the hardware from the environmental effects the components are placed in a waterproof housing. A non-metal enclosure is selected to allow the use of the on-board antenna of the WiseNode. The hardware components are mounted on small plastic boards which are inserted into the enclosure. The plastic board that holds the sensor module is glued to the enclosure to guarantee proper vibration transfer from the stay-cable to the sensor module.

4.2 Field data

Figure 5a) shows the time evolution of the 3rd natural frequencies of the monitored stay-cables of the Stork Bridge. The data logging was started at 6 pm and stopped 24 hours later. The measurement period was 2 minutes. The natural frequency estimations of the cables C1 to C4 are quite constant with a small data scattering. Cable C6 displays a significantly higher data scattering and cable C5 shows relevant changes of the 3rd natural frequency. The data scattering is more pronounced during the night and in particular between 0 and 6 am. During the night time with only little traffic on the bridge, the ambient vibrations of the cables are very small. The natural frequency peaks are therefore much closer to the noise level making the peak identification more difficult and producing an increased scattering in the natural frequency estimations. During day time the traffic induces higher vibrations that produce well distinguishable peaks guaranteeing reliable peak detection.

Cable C5 shows greater scattering of the results when compared to the results from other cables because cable C5 is made of carbon fibre reinforced polymer. Since the damping of this cable is much higher than that of the ordinary steel cables (damping ratio of 2-3% versus 0.5%), the natural frequency peaks are less pronounced and therefore less detectable at very low ambient vibration amplitudes.

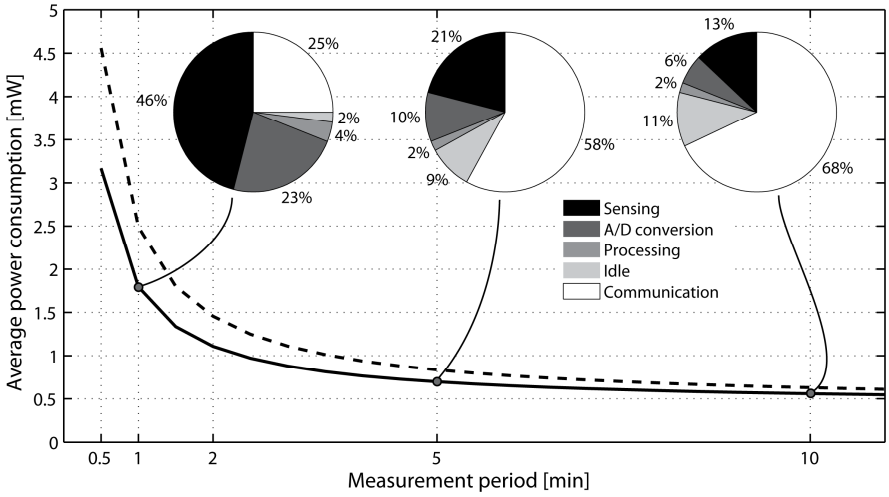

Figure 6: Estimated power consumption of the WSN. The continuous line refers to a packet error rate of 0% and the dashed line to a packet error rate of 20%. The power consumption distribution pie charts are provided for measurement periods of 1, 5 and 10 minutes.

The effect of data scattering can be reduced by post-processing the collected data. Using a moving average filter, the original data set can be smoothed. Figure 5b) displays the smoothed data set of the original dataset presented in Figure 5a). A moving average filter with constant filter coefficients and with a span of 29 values (average over an hour) was used to generate the graphs in Figure 5b). The dotted horizontal lines in Figure 5b) correspond to natural frequency estimations obtained from independent ambient vibration measurements recorded over 5 minutes with a 24 bit data acquisition device and conventional accelerometers. The measurements were performed under very different temperature conditions. The 24h average values obtained with the monitoring system of the cables C1 to C4 coincide well with the results of the independent measurements. In fact, the standard deviations of the monitoring system estimations with respect to the estimations of the measurement M1 are of the same magnitude as the differences between the measurements M1 and M2.

5 POWER CONSUMPTION

The power consumption of a node was estimated by measurements and model computations. Details about the power consumption estimation are found in Novakovic et al., 2009. The power consumption estimate of the last hop node is shown in Figure 6. The power consumption diminishes with increasing measurement period since less data has to be acquired, processed and communicated. With increasing measurement periods the idle power consumption of the node becomes more significant. Figure 6 shows the percentage energy consumption of the different system components for 1, 5 and 10 minutes measurement periods. When acquiring measurements once per minute, the most energy consuming part of the last hop node is the sensor board which contributes with 46% to the total energy consumption. The A/D conversion contributes with 23%, which together with the sensor module makes the process of signal measurement the major energy consumer (75%). Wireless communication consumes 25% of the energy resources of the system. Remarkable is that the energy consumption of the data processing part (4%) is comparable with that of the idle state (2%), which shows that the implemented processing algorithms are very efficient. Further improvements to reduce the algorithms' execution time would not increase the system lifetime significantly.

6 CONCLUSIONS

This paper demonstrates the feasibility of using wireless networks for long term monitoring of civil structures. The proposed system has the potential to achieve a network lifetime of more than a year by using off-the-shelf batteries with a capacity of a few Ah. This goal is achieved by a careful hard- and software design which exploits low power hardware, an energy-efficient communication protocol and signal processing techniques. The investigation showed that the on-the-fly information extraction by in-mote data processing can be performed with nearly negligible power consumption. This paradigm is a key factor for achieving the targeted lifetime since it considerably reduces the amount of data packets that have to be communicated.

7 ACKNOWLEDGMENTS

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