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Wireless Sensor Network for Long-term Structural Health Monitoring of Buildings and Infrastructures

Matthias Bartholmai, Enrico Köppe
Federal Institute for Material Research and Testing, Berlin, Germany

ABSTRACT: Damage commonly occurs in buildings when a component fails suddenly with a partial or total collapse as a consequence. This type of event leads to serious damage to property and if it is a bridge or a large hall, then people in particular are at risk. The often great age of bridges and the increasing volume of traffic (particularly heavy traffic) which they are expected to carry are in clear contradiction to each other. Thus the probability increases that the load-bearing capacity of a bridge decreases rapidly and often unnoticed with sometimes dire consequences.

In order to prevent such accidents, the Federal Institute for Materials Research and Testing is currently developing a special radio-based, self-configuring measuring system in cooperation with the Berlin-based ScatterWeb Company. This measuring system consists of a number of identically designed sensor nodes which are self-sustaining, need no wiring, can act as both transmitters and receivers and are equipped with a special sensor technology making long-term monitoring of buildings or engineering facilities possible. The sensor unit uses strain gauges for stress analysis and contains interfaces for additional sensors. The system in particular applies to buildings and structures for transport and traffic and large-scale industrial facilities, where a subsequent wiring installation is difficult or impossible.

1 INTRODUCTION AND MOTIVATION

Objective of the project is the development of a self-configuring wireless sensor networks (WSN) that allows a long-term structural health monitoring of large-sized buildings and infrastructures using a high number of sensors as described in Bartholmai et al. (2008). The energy-efficient wireless network technology of Berlin's start-up company ScatterWeb was developed to serve exactly this purpose. Thus it offers the ideal platform for the project. The multihop-characteristics should be implemented, which enables the system to over jump malfunctioning sensor nodes and to replace them during operation. Using multihop and repeater function, networks can be established with a number of several hundred sensors. By combining of such a WSN with specific measuring technology (e.g. strain gauges) the overall system is enabled to monitor the structural integrity of various objects, on which wiring is difficult. Examples are transportation structures (bridges and tunnels) and large-scaled plants. For many applications wiring provides extensive problems and causes a great amount of effort and costs and can be even impossible in specific cases

There is a Europe-wide contradiction between the age structure of bridges and the growing traffic volume, particularly heavy load traffic. Cases of damage during the last months and years

demonstrate the need for control mechanisms in regard to stability and durability of buildings and structures. The most effective method to ensure the safe operation and usage of these objects is a permanent structural health monitoring (SHM) using measuring systems with application specific sensors.

The working group Sensors and Measuring Systems of the Federal Institute for Material Research (BAM) and Testing develops a system for early damage detection and structural health monitoring of buildings and infrastructures with high risk exposure in the framework of a research project. The concept of the project includes development, validation and operation of a WSN for strain and stress analysis. Objective is to provide measuring system on a prototype level for a commercial product, which will be merchandised by the project partner ScatterWeb. The system generates a wireless network with self-configuring structure and high network stability. The combination of ScatterWeb's wireless technology and the innovative time differential method for the connection of strain gauges joins two highly energy-efficient technologies for the first time, which provide an optimal basis for the issued task.

In this context specific challenges appear on attributes like reliability, robustness, energy consumption, radio characteristics, user friendliness etc. which must be fulfilled by the system components. At the current state of the project (January 2009) the hardware development is completed, validated and optimized on laboratory level. Actually real application testing is performed and the development of end-user software is carried out featuring system configuration and operation as well as data visualization and management.

2 SYSTEM CONCEPT

The BAM-ScatterWeb System consists of a number of network nodes, which serve as data transmitter and receiver at the same time. Each node combines the radio and the measuring units. Via radio communication the nodes build up a self-configuring network using the license-free ISM Band at 868 MHz. An adequate radio range must be realized to monitor large-sized or difficult to access objects. The multihop architecture (Figure 1) enables data transmission from measuring point to data acquisition unit in multiple steps from node to node, no direct (single hop or point to point) transmission is necessary. Thereby the overall range is maximized and network stability is provided, which allows integration and replacement of single nodes without disturbing the operation of the system.

A wireless system for long-term monitoring using strain gauges requires an energy-efficient circuit design. The presented system is based on an innovative concept of combining radio communication and strain gauge sensors most energy efficient. Therefore an alternative measuring method is used instead of the standard Wheatsone Bridge. According to this highly accurate strain measurements are possible by reducing the energy demand to a minimum.

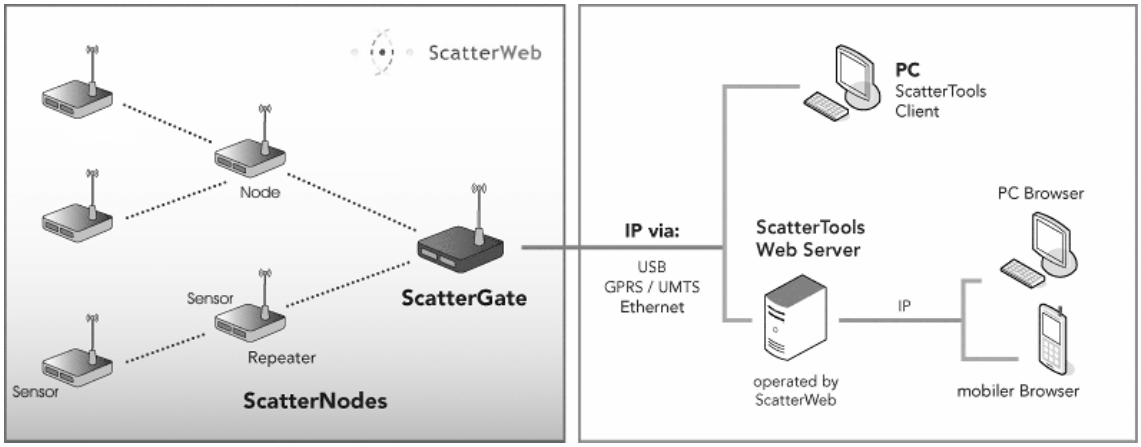

Figure 1. Priciple of the Network Design

3 INNOVATION

Several measuring techniques and equipment solutions for structural monitoring using radio communication are already existent. Most telemetric systems for process and automation technology are particularly designed for high frequency rotating components. Data transmission is realized between a sensor unit on the component and a receiver unit. By this point-to-point and star-shaped connections are possible.

Till now the low-energy utilization of strain gauges, which is necessarily required for long-term monitoring (operation times of several month), still represents an essential problem and is not sufficiently solved to the knowledge of the authors. In the presented project the innovative approach is implemented to combine wireless technology and strain gauge sensors via the time differential method. Instead measuring the relation of resistances by the relation of voltages using the typical Wheatsone Bridge, the difference in discharging times of a precise capacitor is measured. In that way a high-precision strain measurement can be reached by extremely low energy demand. Further advantages are a wide measuring range, high temperature stability and a broad range of application temperature.

For comparison a commercialized system was investigated, which combines radio communication and strain gauge sensors using the conventional Wheatstone Bridge. Results gained, proved that this technology is neither designed nor capable for performing long-term monitoring. Beside for this purpose too high energy consumption and low data resolution, transient oscillation causes problems, which is avoided by using the time differential method. What is more this system does not feature multihop architecture and therefore lacks of communication range. As conclusion the authors feel confident that the new approach in combining multihop networking with the time differential method for operating strain gauges is a very reasonable solution in the field of Structural health monitoring. A patent is pending.

4 IMPLEMENTATION AND SYSTEM DESIGN

The project is carried out in the scope of the MNPQ-Program of Germanys Ministry of Economics and Technology. Objective of the program is the transfer of technology from federal institutions into small and medium state companies.

An important aspect in this program is a system development close to market demands. It is the aim to achieve a functional model which is as close as possible to production and marketing. Hence validation tests under laboratory and real life conditions are important tasks within the project. Besides measuring characteristics of the system the energy efficiency, temperature stability and radio communication are from particular importance in the aspect of validation. The system design is based on longtime experience of developing measuring technology and carrying out specific measuring tasks. Aspects of user friendliness and robustness of the system are as important as technological specifications.

For long-term monitoring the influences of temperature and relative humidity on the measuring system and on the monitored object are of particular importance and are taken into account on the basis of adequate sensors. Each network node includes temperature sensors and/or thermo-hydro sensors. Development of the functional model is implemented in two model types of network nodes - first as an indoor and demonstration device featuring protection class IP54 and operation by two AA cell batteries (Figure 2). This model provides connection of two strain gauge half bridges and one thermo-hydro sensor via soldered joints.

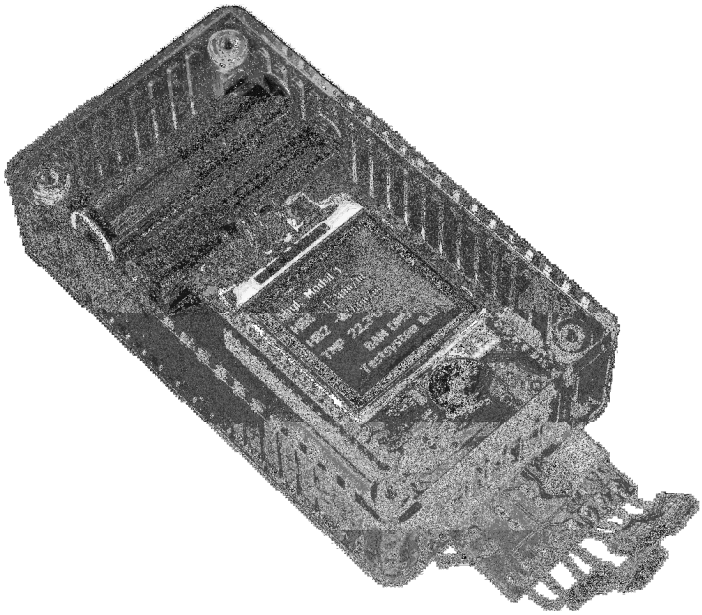

Figure 2. Model layout for indoor and demonstrational use

The second model layout is designed for outdoor usage under weathering exposure and consists of protection class IP66 (Figure 3). It is validated for operating conditions in the range between -30 and +80°C. Two configurations are possible: 8 strain gauge half bridges and 4 temperature sensors or 6 strain gauge half bridges (equals 2 rosettes) and 2 thermo-hydro sensors (for data compensation at each rosette). Connection is implemented via four IP66 plug-and-screw couplings. Standard D-cell batteries allow a service-free operation of more than 6 months.

Figure 3. Model layout for indoor and demonstrational use

Besides possibilities of data acquisition and area of application both model types feature identical operational functions and can be integrated in the same network without circumstances. The Configuration of measuring mode and data handling including sampling rate, offset compensation and validity check can be set directly at each network node. A specific installation mode is implemented. Settings are adjusted via joystick and display (see Figure 2 and 3) to provide handling as easy as possible without additional equipment like PDA or notebook. Data transmission is generally performed via network routing but can also be enabled via USB interface, when a node is operated in single mode without network infrastructure. In network mode a gateway is gathering all sensor and operational data and transfers them to a computer via e.g. cable, WLAN or GSM-Modem. Application software can be used to control the network and to manage and visualize the measuring data for first analysis. Data export to appropriate file types (e.g. Excel, Diadem) for further analysis is implemented.

5 CONCLUSION

Radio based measuring systems will further gain in importance. However their application does not make sense in every scenario and in every context. A reasonable application and using compatible energy efficient components provide the basis for a clear technology advance in specific areas of measurement engineering. Long-term monitoring and early damage detection on critical or difficult to access objects offer convenient opportunities for application of wireless systems but provide challenges at the same time. The presented measuring system features advantages like an easy and cost-efficient installation and service, a user friendly handling and a high technical standard in reliability and accuracy.

References

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