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# Event-based strain monitoring on a railway bridge with a wireless sensor network

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ABSTRACT: This paper presents a monitoring application with a wireless sensor network that was performed on a 95 years old riveted steel railway bridge. In order to perform an accurate assessment, strains were monitored on critical elements to catch the real loading during the passage of heavy freight trains. The wireless sensor network deployed on the bridge consisted of 8 nodes supplied with resistance strain gages and the root node connected to a solar energy rechargeable, battery powered base station. The monitoring system was operated in event-based mode to achieve an energy efficient operation to prolong the lifetime of the sensor network. The event detection was carried out with ultra low power MEMS acceleration sensors, which measured continuously the accelerations of the bridge and detected an approaching train. If this occurred, the sensor generated an interrupt that immediately switched on the strain gage's conditioning board and starts the measurement. Switching on the conditioning board shortly before starting the measurement, however, produces biased raw data because the strain gage was still heating up due to the current flow. Instead of eliminating the time-dependent bias by adding a dummy gage to the Wheatstone bridge, the bias was removed by post-processing the raw data. The paper demonstrates that this procedure provides sufficiently accurate input data for use in cycle counting based fatigue assessment of steel bridges.

## 1 BRIDGE MONITORING

### *1.1 Introduction*

The Haparanda railway line (single track, non-electrified) in northern Sweden has been assessed in order to increase its axle load from 22.5 t to 25.0 tons to enable more efficient freight train transports. The line starts in Haparanda/Tornio, on the border between Finland and Sweden, and goes towards Boden some 130 km in South-West direction. The total length of the line is 165 km. There are plans to build a new railway line in ten years, so the present line only needs to last that long. The initial assessment according to BVH (2000) revealed that some of the bridges did not fulfill all requirements. Most serious was that some of the primary members (stringers and floor beams) would exceed their fatigue capacity. One of the bridges is the one over the Keräsjokk River. The Keräsjoki Railway Bridge is a riveted steel truss bridge built in 1911 (Figure 2). It has one simply supported span with a length of 31.6 m. The railway tracks lies on wooden sleepers directly on the stringers (no ballasting). For this bridge, the initial assessment showed that the fatigue capacity of the web joints in the floor beams would exceed their capacity. This bridge was chosen to demonstrate some of the assessment and monitoring

Figure 2: The Keraesjokk Railway Bridge in Sweden near Haparanda.

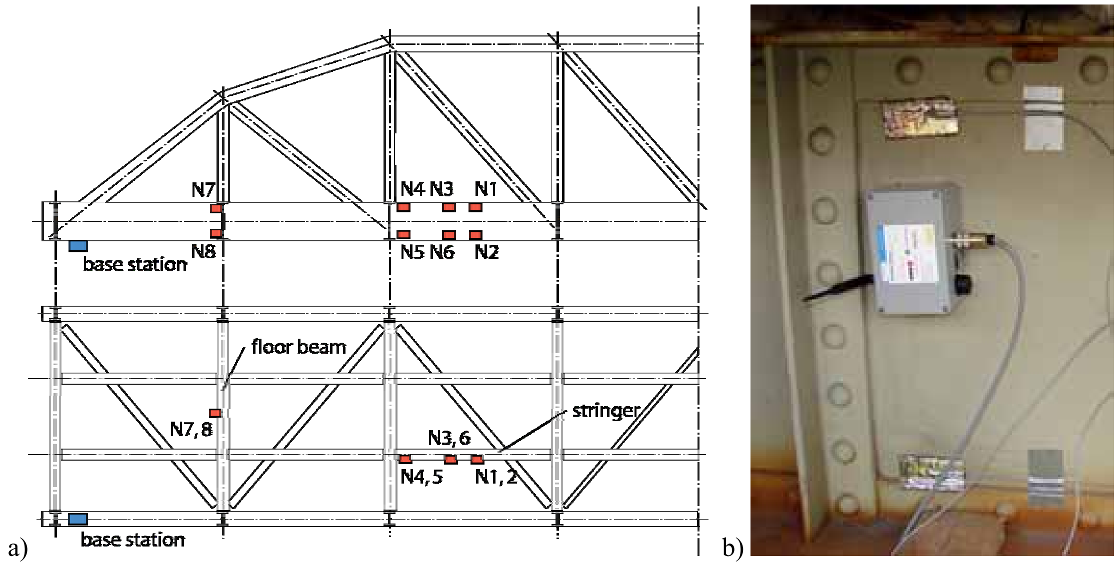


Figure 1: a) Location of strain measurements on the bridge. b) Sensor node and strain gage mounted to the bridge.

methods developed within the project Sustainable Bridges (Olofsson et al., 2004, www.sustainablebridges.net, Enochsson et al., 2008).

### *1.2 Monitoring set-up*

The wireless sensor network deployed on the bridge consisted of 8 nodes and the root node connected to the base station. The location of the strain measurements, all mounted on secondary elements, are displayed in Figure 1a. Six strain measurements, labeled as N1 to N6, were performed on the longitudinal stringer and two measurements, labeled as N7 and N8, were performed on the floor beam. The strain was measured with soldered strain gages featuring a resistance of 120 Ω. Figure 1b shows a deployed sensor node and a strain gage mounted on the stringer (positions N4 and N5).

The strain gages were connected to the nodes of the wireless sensor network by cables, which were plugged into the external connector. The housings of the nodes were equipped with four magnetic footings, which allows for simple and fast mounting. Each node was triggered independently. The sampling rate of data recording was 100 Hz and the record size was 30

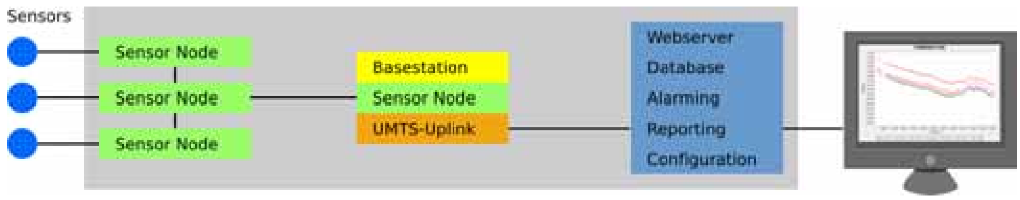


Figure 3: Overview of the wireless monitoring system.

seconds. Since one data item was stored in 16 bit word the total memory requirement of a complete time history was 6 kB or 60 % of the RAM memory of the TI MSP430F1611 microcontroller. The radio communication was periodically switched on and off to save energy. This duty cycle was synchronized over the whole network. Due to this all nodes could still communicate together when the radio transceiver was powered. 90 % of time the radio was shut down and only 10 % of the time the nodes had enabled the energy wasting radio communication. The wake up of the strain gauge signal conditioning unit lasted 100 ms.

All the data recorded by the eight nodes was sent to the base station. To avoid packet collision, a sending policy was introduced where each node has its timeslot when it can transmit its data. The wireless monitoring system recorded also temperature, humidity, supply voltage and network tree data with a time interval of 2 minutes.

The wireless monitoring system was installed on July 24th and removed on July 31st 2007. Since the strain gauges had been installed in advance, the installation was quite fast and took approximately 4 hours. The most time consuming work was the connection between strain gauges and the nodes (soldering of wires, checking of functionality). The bridge was crossed by freight trains driven by diesel engines (one or two) with 220 kN axle load. The trains were composed of different type of boogies.

## 2 WIRELESS MONITORING SYSTEM

### *2.1 Overall architecture*

The monitoring system is composed of three subsystems, which are displayed schematically in Figure 3. The first subsystem is the wireless sensor network (WSN) installed on the structure, which is composed of the sensor nodes, which are the data sources, and the root node, which is the data sink (Culler, 2004). The root node is linked to the base station. The WSN is operated as a multi-hop network where data is forwarded from node to node towards the base station. The routing tree, which is established by the SP protocol (Polastre, 2005), defines the data flow in the network. The routing tree is adapted periodically by assessing the link quality to 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 do not reach directly the base station or if a node stops to operate.

The second 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 Local Area Network (WLAN) or Universal Mobile Telecommunications System (UMTS).

The third subsystem is the remote control center that collects all the data originated by the WSN and is responsible for the long term storage of the data. Furthermore, it implements the data visualization and representation tools for the end users and provides an interface to the operator to observe, control and configure the WSN remotely.

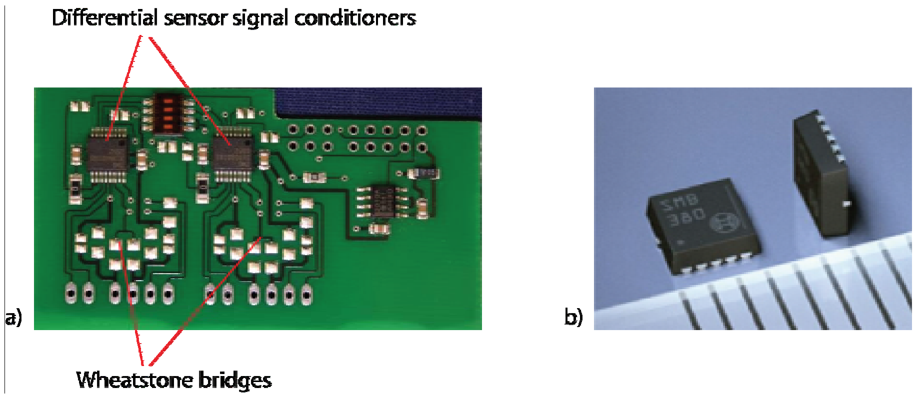


Figure 4: a) Strain gage signal conditioning board. b) Event detection acceleration sensor.

## *2.2 Hardware*

The hardware components of the sensor nodes are the 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 the power supply (Bischoff, 2009). Measuring time series with high sampling rates is energy consuming. It is therefore advisable to sample the measurand only when signals of interest are expected. This often means to sample signals only if a certain amplitude threshold is exceeded. In case of strain measurements this means that dynamic strains are only measured when a train is crossing the bridge. Hence, a train detection mechanism and device was developed, which enables power-consuming measurements only in case of train crossings.

### *2.2.1 Wireless sensor network platform*

The sensor node is based on the commercial Tmote Sky WSN platform (Polastre, 2005), which was chosen because it excels by very low power consumption (5.4 mW at radio-off state and 65 mW in full operational mode). The main components of the Tmote Sky sensor node platform are the ultra low power TI MSP430F1611 microcontroller and the Chipcon CC2420 low power radio chip. The 16-bit microcontroller features 10 kB of RAM and 48 kB of program memory. It has 8 external 12 bit ADC ports with an input that ranges from 0 to 3.0V. 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 that operates in the ISM (industrial, scientific and medical) 2.4 GHz frequency bands. 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.

### *2.2.2 Signal conditioning for strain gauges*

The conditioning board implements a Wheatstone bridge-type signal conditioning for an accurate measurement of electric resistance changes (Figure 4a). The board is equipped with two ZMD31050 differential sensor signal conditioners for operating two independent strain gauges simultaneously. The ZMD31050 allows the amplification, compensation of sensor offset, sensitivity, temperature drift and non-linearity by an integrated 16-bit RISC micro controller running a correction algorithm with parameters stored in a non-volatile EEPROM. These coefficients can be programmed from the wireless sensor network platform during the calibration process. The communication between the signal conditioning board and the wireless sensor network platform is established by the I2C bus. Since measuring with a Wheatstone-

a) 


b) 

Figure 5: a) Base station without cover. b) Base station deployed at the bridge and attached to car battery and solar panel.

bridge circuit is expensive in terms of energy, a power switch allows turning on and off the signal conditioning board in order to safe power.

### *2.2.3 Event detection sensor*

The event detection is implemented with an acceleration sensor. Since this sensor is running all the time, its power consumption has to be very low. We opted for the Bosch Sensortec SMB380, a low cost tri-axial sensor for consumer market applications (Figure 4b). Two features make this sensor particularly useful in this application context: resolution, power saving capabilities with configurable duty cycle and on-chip signal processing capabilities. The sensor has a resolution of about 4 mg at a measurement range of ±2g. The power consumption is 500 μW at full operation mode and 3 μW at sleep mode. The wake-up time is 1ms.

The sensor has a built-in signal processing capability for analyzing the acquired accelerations. This feature can be used for generating an alarm if a specific threshold is violated. The sensor informs the sensor node platform about the violation by setting an interrupt. The alarm criterion is set via the I2C-bus.

The sensor periodically samples the acceleration and it detects the train if a given threshold is exceeded. If this occurs, the sensor generates an interrupt that is serviced by the WSN platform.

### *2.2.4 Base station*

The base station, which collects all the data, was equipped with a low power computer equipped with an ARM processor. The mean power consumption is 4.5 W. The base station was mounted close to one of the abutments. Two 12 V car batteries provided the power supply. The batteries were recharged with a panel of solar cells, which was mounted on the top of the bridge (Figure 5).

## *2.3 Software*

The software running on each node establishes the wireless network, organizes the communication between the nodes, 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 (Levis, 2005)

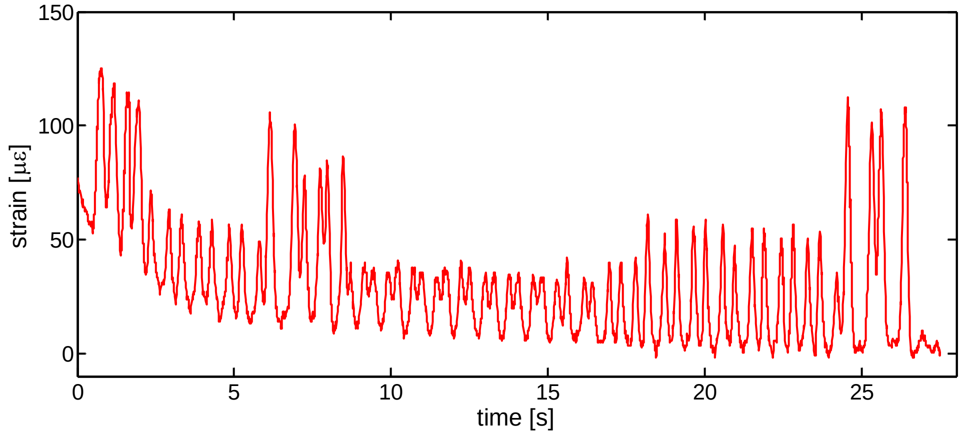


Figure 6: Raw data of a strain measurement at N2 (stringer).

components. The software architecture is discussed in more detail in (Bischoff, 2006, and Feltrin, 2007).

# 3 RESULTS

## 3.1 *Raw data*

A typical recorded time series of the raw data at the measurement point N2 at the stringer (bottom, middle) is displayed on Figure 6. Each axle of the train is clearly visible. The resolution of the strains was found to be approximately 1 με. The accuracy, which could not be tested, was estimated to be approximately ±3 με. The achieved accuracy is good enough for assessment purposes and in particular for fatigue assessment using cycle counting based methods. The time series do not show significant dynamic effects. This outcome is due to the small dynamic amplification factor.

The raw data contains the expected strain cycles generated by the axles passing over the stringer. The raw data, however, are biased by a significant time-dependent signal. The bias was generated by switching on the strain signal conditioning device shortly before the measurement was started. Due to the resistance of the strain gage, the current flow heats the strain gage increasing its temperature and consequently its resistance. The Wheatstone bridge translates this resistance change in a decreasing voltage signal. Since the heat produced in the strain gage flows into the surrounding metal and air, the temperature of the strain gage increases with increasing time until eventually an equilibrium state is achieved.

Figure 6 shows that after 30 seconds from switching-on the strain gage board the equilibrium state was not completely achieved. Conventional monitoring system do not show this bias because they are always operated in the equilibrium state since switching-on occurred long time before the first measurement started and the devices are never switched-off between two measurements.

The bias can be removed by adding a dummy gage in the Wheatstone bridge for achieving temperature compensation (2 gage system). Since the dummy gage is not bonded to the structure, it has to be designed to provide the same thermal characteristics of the primary gage for achieving good temperature compensation. This solution, however, is expensive since the temperature compensation must be adapted for each specific application and complicates the deployment process.

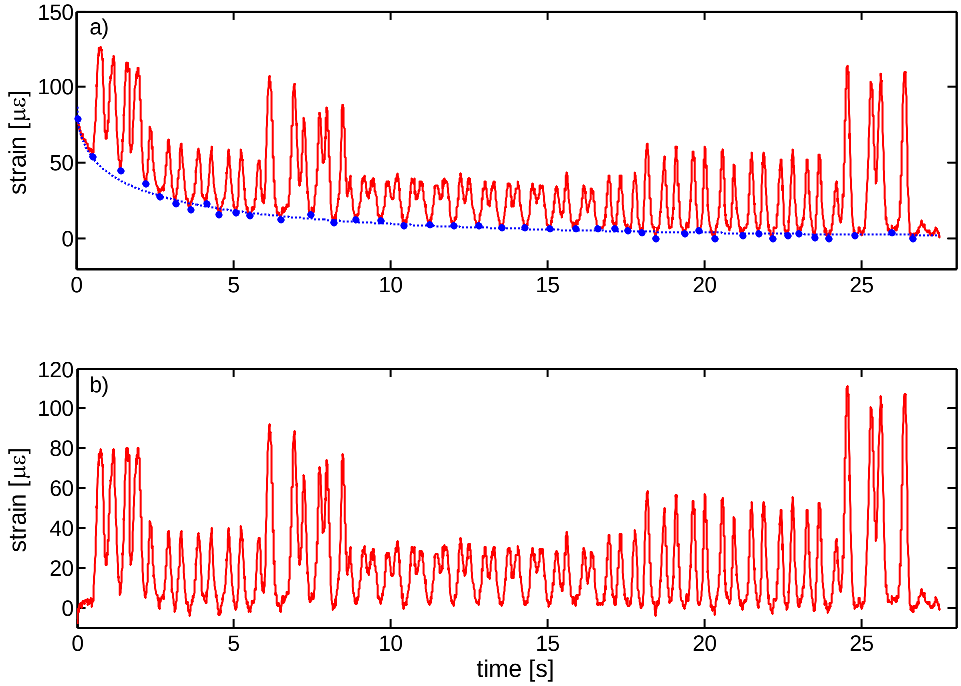


Figure 7: a) Curve fitting for switch-on bias removal. b) Strain after removal of switch-on bias.

### *3.2 Removal of switch-on bias by data processing*

An alternative method is to remove the time-dependent bias by post-processing the raw data. The goal is to fit the bias with a suitable time-dependent function and to remove it by subtracting the fitted function from the raw data. The principle is depicted in Figure 7a). The bias is defined selecting the local minima of the raw data. This approach is justified since significant nonzero strains occurred only when the stringer is directly subjected to the axle loads. Hence, the minima of the unloading phases of the raw data are driven mainly by the non-stationary heating process. Independent measurements performed with conventional strain measurement devices confirm this approach (Kiviluoma, 2007).

A satisfactory fitting of the minima was achieved with a simple exponential function that depends on the square root of time:

$$\varepsilon_b(t) = ae^{-b\sqrt{t}} + c \tag{1}$$

where $a, b$ and $c$ are the fitting parameters. The fitting was performed by a least square fit. The fitted function is shown in Figure 7a) by the dotted blue curve.

The effect of bias removal on strain cycle counting is displayed on Figure 8. The most important differences concern the cycles with large strains. The differences are due to the first 10 seconds of the raw data because in this interval the bias gradient is high and tend to overestimate the amplitude of the cycles. Since the amplitude of cycles are defined by the difference of two value, the cycle counting histograms of raw and processed data do not differ significantly. If the accuracy requirements are not particularly tight, cycle counting using the biased raw data may already provide sufficiently good results for fatigue assessment.

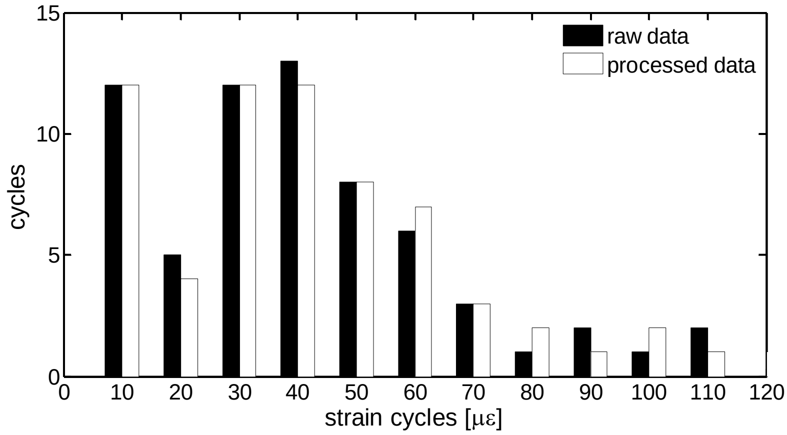


Figure 8: Strain cycles counting of raw and processed data.

## 4 ACKNLOWLEDGMENTS

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