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Strain Cycles Monitoring of Metallic Railway Bridges using a Wireless Sensor Network

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Abstract

As a result of the increasing traffic volume on the European railway network a major concern is the remaining fatigue life of old metallic bridges. Past investigations demonstrated that monitoring enabled more reliable fatigue assessments. In this paper, an event driven monitoring system based on a wireless sensor network that consisted of two functionally different components was designed and tested. Sentinel nodes detected approaching trains and alert monitoring nodes which were mounted on the bridge. After receiving the alarming message, these nodes started strain data recording and went back to power saving mode after completion. An embedded data processing algorithm transformed the recorded raw data into a much smaller data set representing the recorded strain cycles. This data was saved to a base station which transferred the data to a server using the cellular phone network. The test deployment on a railway bridge demonstrated that the monitoring system performed very reliably. The quality of the recorded data was very good. The combination of event driven monitoring and embedded data processing ensured a battery lifetime of five to six months.

Keywords: metallic railway bridges, fatigue assessment, strain cycles monitoring, wireless sensor network, sentinel nodes, event driven monitoring, embedded data processing.

1 Introduction

Due to the increasing traffic volume on the European railway network many existing railway bridges are currently subjected to train loads and speeds that exceed the design values. On metallic bridges higher loads and speeds generate a greater number of high amplitude strain cycles that have an impact of the remaining fatigue life. Past investigations demonstrated that monitoring allowed to perform much more reliable fatigue assessments. [1, 2]. Typically, the monitoring program is

focused on acquiring strain data from critical structural components which are exposed to many high amplitude strain cycles.

Among different concepts and technologies for civil structures monitoring, wireless sensor networks (WSNs) have the attractive properties of being highly automatable and cable-free, thus enabling a rapid and cost-saving deployment. Reduced installation costs favour mainly short and medium term deployments which, in practice, represent the majority of monitoring applications. However, battery-operated WSNs are only competitive if they can provide good quality data and can be operated reliably and with minimal maintenance for a sufficiently long time.

Strain monitoring for fatigue life evaluation of railway bridges are characterized by several peculiarities. Since fatigue assessment is performed by considering only strain cycles induced by traffic loads, the absolute strain usually does not need to be recorded. As a consequence, strain recording is only necessary when a train is crossing the bridge. The monitoring process is therefore event driven. Since on most of the bridges the average time interval between trains are much greater than the average recording period at train crossings the implementation of an event driven data acquisition mechanism is advantageous. By operating the sensor nodes only during train crossings, a significant saving of energy can be achieved which is always an important benefit in long term deployments of WSNs.

2 Strain sensing

Strain measurements on civil structures are usually performed with electrical resistance strain gages. While their use with wired monitoring devices do not present particular problems, operating resistance strain gages with battery powered WSNs rises an important drawback since the power consumption of resistance strain gages is very high. While the typical power consumption of vibration sensing hardware with good quality MEMS accelerometers is about 3 mW, the widely deployed 120 Ω resistance strain gages with a Wheatstone bridge as signal conditioning unit consume approximately ten times more power (ca. 50 mW). This figure is comparable to the power consumption of the radio unit in transmission mode which is the most power consuming hardware component of a sensor node. Therefore, operating resistance strain gages permanently implies a dramatic reduction of the battery lifetime of a sensor node.

Despite their importance in practice, the high power consumption might be the reason why strain monitoring with WSNs has found much less attention compared to vibration monitoring. Nagayama et al. [3] developed a signal conditioning board for electrical resistance strain gages for the Berkeley Mote platform Mica2. The board's resolution of about 4 $\mu\text{m/m}$ was experimentally verified with laboratory tests. Whelan and Janoyan [4] and Bischoff et al. [5] have designed a board for electrical resistance strain gages for the Tmote Sky platform. Both developments were tested with bridge deployments. Recently, Jo et al. [6] developed a high precision strain sensor board for the Imote2 platform that is able to measure low-level ambient strain by precisely balancing the Wheatstone bridge. The sensor board was tested with a field deployment on a cable-stayed bridge.

Power consumption of strain sensing can be reduced by increasing the resistance or reducing the input voltage of the signal conditioning circuit (Wheatstone bridge). The circuit resistance can be increased by using 700 Ω instead of 120 Ω strain gauges. Increasing the resistance, however, reduces the signal to noise ratio. Reducing the input voltage has the drawback to reduce the sensitivity of the signal conditioning circuit which is proportional to the input voltage. Therefore, both power saving methods potentially reduce the data quality.

A signal conditioning board for strain sensing was developed by Feltrin et al. [7]. The key idea was to increase the total resistance of the signal conditioning circuit by adding resistors in series with the Wheatstone bridge. The loss of sensitivity of the Wheatstone bridge due to the resulting drop of input voltage is compensated by a low noise A/D converter with 24 bit resolution that enables to digitalize the signal with a high resolution while keeping a good amplitude range. The main drawback of the 24 bit A/D converter is that it is slower than a 12 bit A/D converters since its sampling rate is limited to 470 Hz. For the addressed application, however, such a sampling rate is very unlikely to be a limitation. With an amplifier gain configured to 128, the amplitude range is approximately $\pm 15'900 \mu\text{m/m}$ and the resolution is smaller than 0.5 $\mu\text{m/m}$. These values comply well with the requirements of strain measurements for fatigue assessment of civil structures.

The power consumption of a sensor node with a signal conditioning circuit without additional resistors, which correspond to standard circuits, and with a 120 Ω strain gauge was about 60 mW. By adding two resistors of 300 Ω each, the power consumption could be reduced to 20 mW. Replacing a 120 Ω strain gauge with a 700 Ω strain gauge produced an additional drop of the overall power consumption to 12 mW which is 20% of the standard hardware power consumption.

By including the resistors in series, the signal noise, as expected, increases and signal conditioning circuits with 120 Ω strain gauges suffer a resolution loss that ranges from 1 bit to 2 bits. The root mean square of noise increases from 0.6 $\mu\text{m/m}$ to 1.4 $\mu\text{m/m}$. Circuits with 700 Ω strain gauges are much less sensitive and display a resolution loss much smaller than 1 bit. A resolution of approximately 1 $\mu\text{m/m}$ rms, which corresponds to 0.2 MPa of stress, is still a very good value for fatigue assessment of civil structures.

3 Embedded data processing

Embedded data processing is a powerful tool for extending the life time of sensors nodes. Power saving is achieved by reducing significantly the data communication of data intensive monitoring applications. In addition, low level data communication reduces data loss due to a congestion of communication channels. The feasibility and advantages of embedded data processing was successfully demonstrated in long term vibration monitoring deployments [8, 9]. A strategy for fatigue life estimation for WSN with embedded data processing was proposed by O'Connor et al. [10]. Strain data was continuously acquired and processed by an embedded rainflow counting algorithm. Laboratory tests showed good agreement between the cycle counting histograms obtained by embedded and offline processing.

In this work, embedded data processing computes local minima and maxima of recorded strain data that exceeds a given threshold [7]. The algorithm works like a filter that eliminates all cycles that are smaller in amplitude than the specified threshold. Small amplitude cycles are very often irrelevant since in fatigue assessment methods the impact of small amplitude cycles is usually negligible. Furthermore, such a threshold eliminates all cycles which are generated by signal noise as well. The output of the cycle filtering algorithm can be used by a cycle counting algorithm (e.g. rainflow counting algorithm) to determine the statistics of the cycle's amplitudes. The rainflow algorithm can be easily run on the data server. This choice keeps the embedded data processing on the sensor node simple, straightforward and finally more reliable.

The outcome of the cycle filtering algorithm is displayed in Figure 1. Typical strain time history shows that each axle passing over a cross beam produces a strain cycle. The original record was sampled with a sample rate of 123 Hz and consists of 1476 data points. The extremal points identified by the algorithm are plotted with markers. The cycle filtering threshold was 5 $\mu\text{m/m}$.

Figure 1: a) Raw strain record on a cross beam with local extrema. b) Reduced data set consisting of strain cycles.

The essential information of this event is contained in the 33 extremal points (Figure 1b) which corresponds to 2.3% of the original data size. Although significantly smaller in size, the strain cycles maps the original record with high fidelity. Such a dramatic data reduction is typical for fatigue monitoring applications. By keeping only the extremal points the time information is lost. However, since for fatigue assessment only the amplitude and frequency of strain cycles are of concern, the loss of time information is negligible.

4 Event driven monitoring

Since data acquisition is only required while trains are passing on a bridge, keeping the strain sensing hardware turned on all the time is very inefficient in terms of power consumption. Most of the time, the monitoring system would acquire useless data that would eventually be discarded. A much better policy is to operate the strain

sensing hardware only if there is an event i.e. a train that is crossing the bridge. Such an event driven monitoring policy requires an auxiliary sensor node that is specialized in detecting approaching trains.

Figure 2: Concept of event driven monitoring with sentinel node

The concept of such event driven monitoring systems is sketched in Figure 2 where the auxiliary sensor node is referred as sentinel node. When it detects an approaching train, it immediately notifies the monitoring nodes regarding the upcoming event. The alarming message has to be delivered to all monitoring nodes. The monitoring nodes are usually operated in sleeping mode to save energy. They wake up periodically, switch the radio on and check for alarm messages. In case of no alarm message they go back to sleeping mode. Only upon receiving an alarm message, they turn on their strain sensing hardware and start recording data according the specified data acquisition protocol. Once recording is completed, they switch off the strain sensing hardware and go back to the sleeping mode.

Event driven monitoring requires that the event detection is reliable and the alarming is reliable and fast. In case that the sentinel node misses to detect an approaching train all monitoring nodes will completely miss the event. If some of the monitoring nodes do not receive the alarming message, they will fail to capture the event. In case of a late arrivals of alarming messages, nodes would turn on the strain sensing hardware only when the train has partly or fully passed the measurement points. These failures cause data loss that may bias the fatigue assessment process. On the other hand, false alarms, i.e. sentinel node detects a train but actually there is no train, have to be reduced to a minimum since such false alarms would increase battery consumption both by spreading the alarm through the network and by recording useless data.

4.1 Train detection

Train detection can be achieved by sensing the vibrations or the noise that is produced by an approaching train. Proximity sensors could be used for detecting passing trains as well. Since sentinel nodes have to operate permanently, their power

consumption has to be comparable to those of monitoring nodes being operated in event driven monitoring mode in order to achieve a similar lifetime. A frequent battery replacement of sentinel nodes would impede the practical implementation of this event driven monitoring concept.

In this investigation, vibrations of the rails were used to detect approaching trains. Vibrations can be sensed with MEMS acceleration sensors. Since accuracy is not of concern, cheap MEMS acceleration sensors which are widely implemented in mass electronic products such as smart phones can be used. Their power consumption is typically in the range of less than a mW. In this study, train detection is achieved with the commercial accelerometer Colibrys MS7002 that has an amplitude range of $\pm 2g$ and a resolution of 1 mg. This low power MEMS capacitive sensor has a power consumption of less than 0.6 mW.

4.2 Alarming mechanism

Spreading alarming messages through a multi-hop network in a timely manner is a challenge. Since the radio device is the dominant power consumer of a sensor node it is usually operated with duty-cycling which tends to prolong message delivery. Furthermore, during the alarming, a train is between the sentinel node and the monitoring nodes. Field experience demonstrated that passing trains have a significant impact on the communication link quality between nodes and can affect the reliability of message delivery. In this study, we have decided to use broadcasting of the alarming message rather than unicast transmission. Unicast transmission with acknowledgment is very reliable but much slower than broadcasting.

The alarming message protocol is now briefly sketched. The sentinel node creates an alarm message which contains a sequence number that identifies uniquely the event. This message is broadcasted to the nodes within the radio range of the sentinel node. All nodes that received the message check whether it is a new event by using the sequence number. In case of a new event the nodes rebroadcast the message to their neighbouring nodes. For the purpose of increased reliability in delivering alarm messages, each node will rebroadcast message up to N times. The higher the number of retransmission N the higher is the reliability that the alarming message is eventually delivered. However, a high retransmission number N implies also a high power consumption since radio communication is very expensive. Laboratory tests demonstrated that 3 retransmissions achieved a reception rate higher than 99.5%. Although higher number of retransmissions leads to reception rates that are closer to 100%, their costs in terms of power consumption compared to the gain in reliability do not justify their use.

5 Field test

The field test has been performed on a steel railway bridge near Wila in Switzerland (Figure 3). The bridge has been constructed in 1946 and crosses the river Töss. It has a span width of 36 m and is made of two lateral longitudinal trusses which are

connected with six cross-beams. The bridge carries one rail that is used for trains travelling in both directions. The route is mainly used by suburban trains with sparse events that belong to service trains. Due to nearby train station in Wil, the speed of the trains do not exceed 80 km/h.

Figure 3: The monitored railway bridge of the river Töss.

5.1 WSN platform

The wireless sensor network is based on the commercial sensor node of the company Decentlab GmbH [11]. The core of the sensor node is the commercial ultra-low power microcontroller TI MSP430 of Texas Instrument with 256 KB of flash memory, 8 KB of RAM memory and 16 MHz CPU speed. Wireless delivery of data is enabled using low-power radio transceiver working in European SRD Band from 863 to 870 MHz. The nominal transmission rate is 20 kbit/s. The sleep mode current consumption is 0.6 μ W, while during reception and transmission the consumption reaches 27.6 mW and 51 mW, respectively. The platform features a voltage stabilizer that provides a constant input voltage. Fading batteries or voltage fluctuations due to temperature changes do not have any effect on the data quality.

5.2 Monitoring set-up

The deployment consisted of 2 detection nodes, 3 relay nodes and 6 sensor nodes, one for each cross girder, and the base station (Figure 4). In order to capture trains approaching from both directions, two sentinel nodes have been deployed. They are placed at about 50 m and 85 m away from the bridge. The distance between the sentinel node and the bridge is imposed by the requirement that monitoring nodes start data acquisition before the train reaches the bridge. To avoid generating two events for each train, the sentinel node that is further away from the approaching train will be prevented to generate an alarm within 30 seconds from the time it received the alarm generated by the sentinel node that detects the approaching train first. The accelerometer for train detection was mounted on the rail (Figure 5a) with magnetic footings.

Figure 4: Overview of the deployment.

Each of the six cross beams on the bridge are monitored with commercial strain checkers equipped with $120\ \Omega$ strain gauges [12]. Similarly to sensor nodes that are equipped with magnetic footings and allow deployment within couple of minutes, strain gauge is hitched to the bridge using magnets (Figure 5b). They are placed in the middle of the cross-beam where the highest strain is expected.

Figure 5: a) Accelerometer for train detection mounted on the rail. b) Strain checker and monitoring sensor node mounted on a cross beam.

Due to the lack of line of sight and the electromagnetically highly reflexive metallic structure of the bridge the communication between sentinel nodes and monitoring nodes was unreliable. Therefore, three relay nodes were placed in order to create a reliable link between the monitoring nodes, sentinel nodes and the base station. All nodes are powered with two type-D batteries that provided 1.8Ah at 3 V.

The base station collects all the data of the local monitoring network and forwards the data to a remote server via GSM. It has an average power consumption of 250 mW and was therefore powered with a car battery with a capacity of 78Ah at 12 V. It is deployed around 70 m distance from the bridge next to the rails since this location is not accessible to pedestrians and cyclists which use the road along the river that passes under the bridge.

5.2 Operation mode

The sentinel nodes recorded rail vibrations permanently with a sampling rate of 123 Hz. The acquisition period for a single buffer was 0.2 seconds. The acquired data was continuously analysed by embedded data processing and compared against a threshold of 7 mg. Threshold exceedance in two consecutive buffers generated an alarm message.

After receiving the alarm message and switching on the strain sensing hardware a monitoring node waited 0.6 seconds before starting data collection. This delay was implemented to avoid the initial signal bias due to heating of strain gauges and charging of capacitors in filter circuits. Strain was then recorded with a sampling rate of 123 Hz for approximately 9 seconds. Data were organized in alternating data buffers with a size of 384 samples which correspond to roughly 3 seconds of measurements. While one buffer was filled with new data, the buffer with previously recorded data was forwarded to the embedded data processing pipeline. The first data processing step was a simple check whether the difference between the maximum and minimum values of a record was greater than a given threshold. If the threshold was not exceeded, the data was discarded. This may occur if train passes in less than 6 seconds so that the last data buffer would not contain any valuable data. If the threshold was exceeded, the second processing step calculated the local extrema. The cycle filter threshold was set to a strain of 5 $\mu\text{m/m}$ which is much greater than the noise level and corresponds to a stress of 1 MPa. The result was then forwarded to the radio for transmission to the base station. All nodes reported battery voltage, information about alarming such as time of arrival and number of hops and data regarding link quality and routing of data packets.

6 Results

6.1 Strain data

An unprocessed record acquired on a cross beam with a sensor node is shown in Figure 6. This record was performed prior to the start of the monitoring phase with embedded data processing in order to evaluate the quality of the raw data. The strain cycles induced by the bogies are clearly distinguishable. The record demonstrates that the signal quality is quite good. In fact, the noise is approximately 1 $\mu\text{m/m}$ rms.

A typical example of processed data provided by the monitoring system is displayed in Figure 6. The train was similar to those that generated the record displayed in Figure 6. The 4 bogies are clearly distinguishable. Also the patterns of the cycles agree well with the unprocessed record. With a filter threshold of 5 $\mu\text{m/m}$ the average data size sent over the radio was 9 % of the original raw data size. By increasing the filter threshold, the many small amplitude cycles in front and rear of the main cycles, which are due to vibrations, could be removed with the beneficial effect to further reduce the data size sent over the radio.

Figure 6: Strain record and processed data.

6.2 Alarming efficiency

Alarm information reports provided crucial information about route of alarm messages, the average hop distance until destination and the time at arrival. The time of arrival allows computing the time that alarm messages needed to arrive at destination (monitoring nodes). The time delay histogram is depicted in Figure 7. The median (50% quantile) time delay was 0.13 seconds and the time delay of the 99% quantile was 0.31 seconds. By considering the time delay for starting data acquisition after receiving the alarm message the total delay is about 1 second. At a speed of 80 km/h, the train needed approximately 2 seconds to reach the bridge if we assume that the alarm message was sent when the front of the train reached the location of the sentinel node. Therefore, message delivery was in time.

Figure 7: Histogram of occurrence rate of time delay of alarming messages.

Figure 8a) shows that the hops numbers with the highest occurrence rate are 2 and 3 and the hops numbers greater than 10 are very unlikely. The median is 4 hops. As expected, the average time delay increases with increasing number of hops (Figure 8b). Since alarming message delivery with hops numbers greater than 10 are very few the average value is less reliable.

Figure 8: a) Histogram of occurrence rate of hops. b) Relationship between time delay of alarming messages and number of hops.

6.3 Event hit rate

The number of events occurring during the monitoring period was 3728. Out of these events, of 11 events (0.3%) no data was received from any of the nodes. These events were estimated by analysing gaps in the sequence numbers that are generated by the nodes when new data is acquired. Since the associated alarm reports are missed also by the sentinel nodes, authors assume that the network was working correctly but the data was lost either at the base station or on the server. Figure 9 shows the histogram of the number of monitoring nodes reporting alarm reception at the events.

Figure 9: Histogram of the number of monitoring nodes reporting alarm reception.

It demonstrates that at nearly all (98.6%) remaining 3717 events all monitoring nodes reported an alarm message reception. The total number of incomplete events, these are events that there is no data of at least one monitoring node, is 50 (1.4%).

6.4 Power consumption

Figure 10a) shows the battery voltage status of sentinel, monitoring and relay nodes. As expected, the sentinel node had the highest power consumption due to the permanent data acquisition. The power consumption of the monitoring nodes is very similar to those of the relay nodes. Since relay nodes have to receive and forward the strain data of all monitoring nodes they consume more power for communication than the monitoring nodes. This extra power consumption seems to correspond approximately to the power consumption of strain sensing of the monitoring nodes.

The voltage drop during 45 days is 0.3 V. Since the sensor nodes operate correctly for a battery voltage greater than 1.8 V the expected life time of sensor nodes is 5 to 6 months. Figure 10b) shows the battery voltage of the base station. After 45 days the voltage of the car battery dropped by 0.4 V. By considering 9 V as the limit when the cellular modem would stop working the expected life time of the base station is about 12 months.

Figure 10: Time evolution of battery voltage of nodes (a) and base station (b).

7 Conclusions

This paper investigated a WSN for monitoring strain cycles on railway bridges. It uses an event driven data acquisition policy for saving power and extending the lifetime of the monitoring system. Sentinel nodes located in front of the bridge detect approaching trains and inform the monitoring nodes regarding the event by broadcasting alarm messages. The monitoring nodes perform data acquisition only after receiving the alarm. Between alarms they are operated in low-power mode.

The concept was tested with a field test on a railway bridge that lasted for 47 days. The test demonstrated that train detection as well as alarming performed quite reliably. In only 1.4% of the events at least one monitoring node did not receive the

alarm message. Only 0.3% of the events were missed by all monitoring nodes. This is a rather small failure rate for a very first deployment. Alarm message delivery turned out to be fast so that data loss due to late arrival of alarm messages can be minimized.

The estimated lifetime of sensor nodes for the specific deployment was 5 to 6 months. A replacement of batteries twice a year would be acceptable for practical deployments. In many cases 5 to 6 months of monitoring data would already provide a very good data base for a reliable fatigue assessment. The test demonstrated once more that the data quality that WSN can provide complies by far the requirements of civil engineering.

Although there is still space for improvements, this investigation demonstrates that a wireless sensor network is well suited for performing efficiently and reliably strain cycles monitoring of metallic railway bridges.

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