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Wireless strain sensing system for assessing condition of civil infrastructure facilities

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Professional paper

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Wireless sensors and sensor networks are emerging as substitutes for traditional structural monitoring systems. Their benefit lies in a lower cost of installation because extensive wiring is no longer required between sensors and the data acquisition system. Studies carried out to evaluate performance of wireless strain measurement units are described in this paper. An example is given of a wireless system used for measuring behaviour of a railway bridge, and comparison with traditional systems is made.

Key words:
Wireless sensor networks, strain, LabVIEW, wireless nodes, wireless gateways

Stručni rad

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Bežični sustav mjerenja relativnih deformacija za ocjenu stanja infrastrukturnih građevina

Bežični senzori i senzorske mreže postaju zamjena za tradicionalne sustave za praćenje ponašanja konstrukcija. Njihova je prednost u nižoj cijeni ugradnje jer nema potrebe za polaganjem dugih kabela između senzora i sustava za prikupljanje podataka. U radu se opisuju istraživanja provedena u svrhu ocjenjivanja učinkovitosti bežičnih senzora za mjerenje relativnih deformacija. Dan je primjer primjene bežičnog senzorskog sustava pri mjerenju ponašanja konstrukcije željezničkog mosta te je napravljena usporedba s primjenom klasičnih sustava.

Ključne riječi:
bežične senzorske mreže, relativna deformacija, LabVIEW, bežični čvorovi, bežični poveznici

Fachbericht

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Drahtlose Messsysteme für relative Verschiebungen bei der Beurteilung von Infrastrukturbauten

Drahtlose Sensoren und Sensornetze werden zum Ersatz für traditionelle Systeme zur Beobachtung des Verhaltens von Tragwerken. Ihr Vorteil liegt bei den tieferen Installationskosten, da das Verlegen langer Kabel zwischen Sensoren und Datenerfassungssystemen nicht notwendig ist. In dieser Arbeit werden Untersuchungen, die sich mit der Beurteilung der Wirksamkeit drahtloser Messsensoren zur Messung relativer Verschiebungen befassen. Ein Beispiel zur Anwendung des drahtlosen Sensorsystems bei Messungen des Tragwerksverhaltens einer Eisenbahnbrücke ist dargestellt und ein Vergleich mit der Anwendung klassischer Systeme ist gegeben.

Schlüsselwörter:
drahtlose Sensornetze, relative Verschiebungen, LabView, drahtlose Knoten, drahzlose Anschlüsse

1. Introduction

Our daily lives are becoming more and more dependent on civil infrastructure, including bridges, buildings, pipelines, offshore structures, etc. It is very important to monitor the condition of such structures, as the monitoring activity enables their proper maintenance. The evaluation of structural condition is highly important after natural hazards such as earthquakes, and after man-made disasters such as terrorist attacks. The condition of such structures has to be evaluated without delay, and they have to be repaired at once to minimize the impact of the disaster and to facilitate recovery of the affected local population and wider community. Tragic disasters, such as the collapse of bridges or residential buildings, often result in a large number of casualties, and generate social and economic problems. The structural health monitoring (SHM) is an emerging field in civil engineering offering various possibilities for the continuous and periodic assessment of the safety and integrity of civil infrastructure. Damage detection strategies can ultimately reduce total costs, i.e. cost incurred over the entire life cycle of structures. In general terms, damage can be defined as changes introduced into a system that adversely affect its performance. Most structural health monitoring methodologies require direct measurement of input excitation for the monitoring to be effective. Methods based on ambient vibrations have gained a considerable importance in the field of structural health monitoring and in detecting the level of damage. An additional challenge arises from the fact that damage in structures is an intrinsically local phenomenon. Sensors close to a damaged site are expected to react better to damage compared to more distant sensors. Therefore, sensors must be densely distributed throughout the structure to effectively detect the place of damage at a point within the structure. It is quite challenging to use traditional wired sensors to implement such a structural health monitoring system based on a dense array of sensors because of the difficulties in deploying and maintaining the associated wiring. In addition, managing such a large amount of data is complex and is not cost-effective. Recent achievements in the development of wireless sensors have enabled implementation of the SHM procedure using a dense array of sensors. Such dense arrays of low-cost wireless sensors can improve the quality of structural health monitoring quite significantly, as these sensors enable wireless communication. Such wireless sensors provide a great quantity of data that can further be utilised by structural health monitoring algorithms to detect, locate, and assess structural damage caused by severe loading events. The information obtained from densely instrumented structures is expected to provide a better insight into the physical state of structural systems.

Studies carried out to evaluate performance of wireless sensing units for strain measurements, and development of the associated real time data-acquisition software, are described in detail in this paper. The wireless sensor system was successfully deployed at a railway bridge site, where various structural performance parameters were evaluated, and comparisons were made with parameters obtained by numerical simulations.

2. Wireless sensor networks - system overview

Wireless Sensor Networks (WSNs) can be described as a class of information technology infrastructure where computations are embedded into the real-life physical world. Wireless sensor networks consist of a large number of spatially distributed devices known as smart sensors, which are characterized by computing and sensing capabilities. Wireless sensor networks are used for monitoring condition of structures, environmental influences, traffic, manufacturing and plant automation [1, 2]. They consist of appropriately distributed and wirelessly enabled embedded devices in which a variety of electronic sensors can be used. Each node in a wireless sensor network is equipped with one or more sensors and with a microcontroller, wireless transceiver, and energy source. The microcontroller functions with electronic sensors and as a transceiver, and so an efficient system is formed for relaying small amounts of important data with a minimum power consumption. When deployed in the field, the microcontroller automatically initiates communication with every other node in the range, thus creating an ad hoc mesh network for relaying information to and from the gateway node. This eliminates the need for costly and complex wiring between systems, and also provides flexibility of mesh networking algorithms to transport information from node to node. This allows nodes to be deployed in almost any location and offers flexibility of monitoring a large number of structures, which greatly increases the possibility of using appropriate structural health monitoring solutions [3-5].

The wireless sensor network has been developed to address limitations of the existing structural health monitoring techniques, which rely on either periodic visual inspections or expensive wired data acquisition systems. With the wireless sensor network platform, users can easily monitor condition of structures or environment using reliable, battery-powered measurement nodes that satisfy industrial ratings, and local analysis and inspection requirements. The wireless sensor network system by National Instruments (NI), which was used in this research, is based on the IEEE 802.15.4 wireless mesh network. The wireless sensor network consists of three main components: nodes, gateways and software. The spatially distributed measurement nodes interface with sensors to monitor structures. The acquired data wirelessly transmits to the gateway, which can operate independently or is connected to a host system where the user can collect, process, analyse and present measurement data using an appropriate software. Routers are a special type of measurement nodes that can be used to extend distance and reliability of the wireless sensor network.

2.1. Wireless sensor network gateway

In a wireless sensor network system, the gateway acts as the network coordinator in charge of node authentication and message buffering. The gateway collects measurement data obtained from nodes and sends them to the company network, where the user can collect, process, analyse, and present the measurement data using a variety of software. The user can use multiple gateways, each communicating on a different, non overlapping software-selectable wireless channel. The NI 9791 programmable gateway, which is used in this research (Figure 1), operates by running deployed LabVIEW real-time applications. The NI WSN-9791 ethernet gateway is a pass-through device that must be connected to a host system. This gateway has a 2.4 GHz IEEE 802.15.4 radio to collect measurement data from the sensor network.

Figure 1. Wireless sensor network gateway

2.2. Wireless sensor network measurement nodes

The following properties are highly significant for wireless sensor network measurement nodes: direct sensor connectivity, reliable communication, and satisfying ratings for use in industry. As nodes are programmable, LabVIEW can be used to customize node behaviour and, adding intelligence, perform local analysis and control. The NI WSN-3214 strain measurement node (Figure 2), which brings waveform acquisition capabilities to the wireless sensor network product line, is ideal for wireless structural health monitoring applications. The node features four analogue channels that support quarter-, half- and full-bridge completion, as well as two digital I/O channels for event detection and programmatic control. A 2.4 GHz radio is used to wirelessly transmit data to the wireless sensor network gateway. The wireless sensor network node can also be configured as a mesh router to increase network distance and connect more nodes in the wireless sensor network system. The node provides 2.5V excitation and supports 350 W and 1 kW strain gauges. When a node powers up, it scans for available networks, locates either a gateway or router node, and attempts to join. When the node joins the network, it downloads the latest configuration from the gateway and begins its normal operation of acquiring measurement data, controlling digital input/output, and transmitting data back to the gateway for processing, alarming, and visualization.

Figure 2. Typical wireless sensor network measurement node

3. Development of strain measurement program

Studies were carried out towards development of software for wireless data acquisition in the scope of the wireless sensor network, using the LabView interface. National Instruments offers its Measurement & Automation Explorer (MAX), a graphical user interface, to configure the wireless sensor network. This measurement & automation explorer is usually installed with one of the NI application development environments such as LabVIEW or Measurement Studio, or with one of the NI hardware product drivers. The measurement & automation explorer is used for configuring the measurement nodes and the gateway. The connection status of the wireless sensor network is verified in the measurement & automation explorer. The configuration settings like addition, removal and modification of wireless sensor network nodes are performed in the explorer. Applications developed in LabVIEW are encrypted with a unique ID and Password. The login & configuration section consist of a user-friendly login with information regarding the authentication details, and the path of the acquired data file to store. After entering the main login screen, the user has to provide the path where the configuration and test data will be saved for further reference. After setting the path, the node status window pops up and there the battery state, link quality, network mode, etc. is displayed as shown in Figure 3. The user interface of the developed program has login & configuration options, display settings, and options for the real time data acquisition and display, networking, and post processing (Figure 4). The configuration setup helps in incorporating the configuration of the sensors by reducing the operation time. The configuration icon in the menu screen is used for the node configuration settings. The start icon is used to start the test. The online monitor icon is used to view the data acquired from the wireless sensor network node when the test is being carried out. The user icon is used to add a new user, or to remove the existing user. The offline viewer is used to view the data for analysis after the test is completed. The help icon is used to help the user to find out more about the measurement system and parameter settings. The offset button is used to initialize the strain value. The node status button is used to view the status of the node.

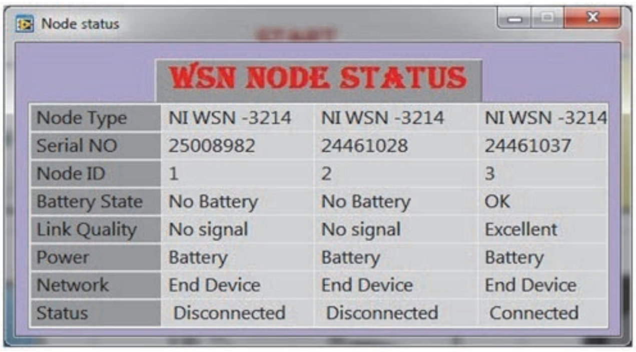

Figure 3. Node status window

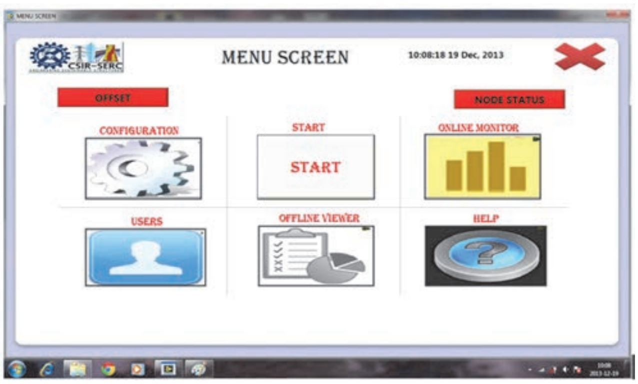

Figure 4. Main screen of developed program

The developed program also enables selection of various configurations for strain measurement. The excitation voltage, measurement range, and bridge configuration settings are also incorporated for each channel and can easily be selected. Each node of the wireless sensor network is configured according to the activation period of the node. The scheduling and data logging of the node is also incorporated. Each channel can be configured to acquire data through a different bridge configuration depending upon the requirements, i.e. quarter bridge, half bridge, and full bridge. Then the parameters like the node, channel number, bridge type, gage factor, Poisson ratio, sampling rate, and waveform interval, are assigned. At that point the settings have to be saved (Figure 5). The developed program also has options for an offline analysis of recorded data, at any point in time. The offline viewer icon is used to view the test data after the test is stopped. Topology plays an important role in the wireless sensor network. Several types of topology can be differentiated in the wireless sensor network system. The topology configuration helps in deciding which node would be acting as the router or the node itself. From the topological standpoint, each node can act as a router and forward the data to the gateway node. Some of the topologies developed in the program are egalitarian topologies (Peer to Peer, or Point to Point), and Star-, Tree-, and Mesh-based topologies.

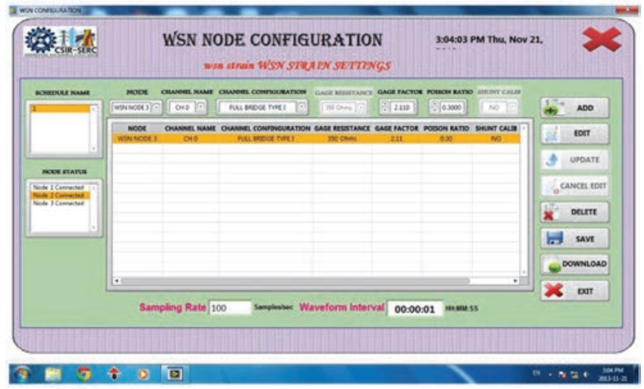

Figure 5. Wireless sensor network configuration settings

4. Performance evaluation for measurement nodes and developed program

The performance of the measurement nodes and the developed program needs to be evaluated under the real time testing environment. Laboratory level calibration studies were therefore carried out using the wireless sensor network for known loadings. For this purpose, a cantilever was instrumented with strain gages along the longitudinal and transverse directions. These strain gages were connected to the wireless sensor node in various bridge configurations. The cantilever beam was subjected to known loads, and strains were measured through the wireless nodes (Figure 6).

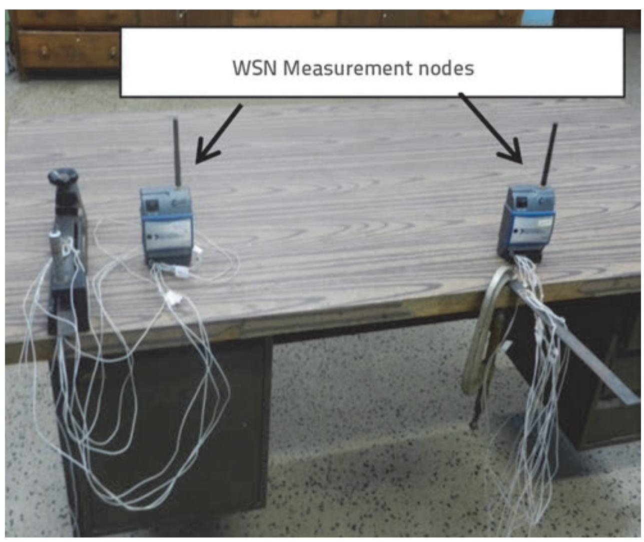

Figure 6. Strain gages connected to wireless sensor network (WSN) measurement nodes

The measured strains were transmitted wirelessly to the gateway, and the data were viewed in real time on the host personal computer. Hence the software was able to collect the data from wireless sensors through the gateway, and also to plot the data in real time (Figure 7). Thus the application developed for this purpose was able to receive the data from NI measurement nodes wirelessly, and to present the acquired data in real time on the host PC. Additional studies were carried out to evaluate performance of measurement nodes. The strain gages placed on the cantilever beam were connected to a standard conventional data logger in the same configuration. Known loads were applied to the cantilever and the strain was measured at the data logger. The measured strains were compared with the strains measured via wireless nodes. A good correspondence of these strain values was established, with the variation in measured strain of less than 2 %. Hence the measurement nodes were found to be suitable for structural health monitoring applications.

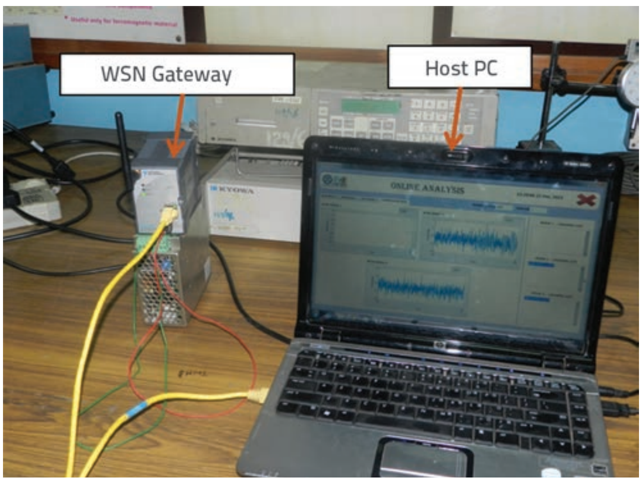

Figure 7. Real time data plot at Host PC

5. Bridge monitoring using wireless strain sensing system

Performance of the wireless sensor system was evaluated in laboratory conditions. Responses measured from wireless sensors were compared with those of conventional sensors. The responses were matching well and hence the wireless sensor system was used for assessing condition of a railway bridge. The condition assessment was carried out on the pre-stressed concrete bridge consisting of simply supported spans, as shown in Figure 8. The middle span, measuring 12.9 m in length and almost 1.68 m in depth, was selected for this evaluation. The bridge span consists of two prestressed girders. Each girder is an I-section with seven tendons for effective pre-stressing. Strain gages were placed at five positions, i.e. at quarter spans, at the mid-span, and at supports (Figure 9). The strain gages were connected to the wireless nodes (Figure 10). In addition to the wireless system, a conventional system was also used to enable comparison with the wireless system.

Figure 8. Railway bridge site for deployment of wireless strain sensing system

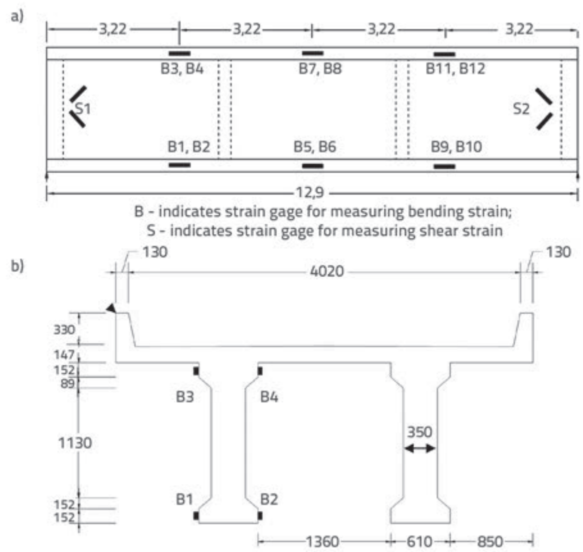

Figure 9. Strain gage locations: a) measurement points during testing of prestressed concrete bridge; b) typical cross-section of prestressed concrete bridge

The test train formation consisted of two front WAG5 locos, BoxN wagons loaded with iron ore, a BV-cabin, and a rear loco. Since it is very difficult to evaluate dynamic bending moments that are induced in a bridge due to movement of trains, static tests were conducted to evaluate calibration factors for converting the measured dynamic strains into bending moments. Three static tests were conducted by positioning the loco and heavily loaded wagons at predetermined locations within the span. Calibration factors were obtained by correlating the maximum static strain values measured at various sections with the corresponding theoretical bending moment. The average calibration factor of 12.85 obtained from the static test was used in dynamic tests to evaluate structural parameters (Table 1). Dynamic tests for ambient running conditions were performed on the bridge, and the corresponding strain responses were acquired. Measured

Table 1. Evaluation of calibration constant from static tests

Static load case	Theoretical bending moment [kNm]	Bending strain [μm/m]	Calibration factor for unit microstrain	Experimental bending moment [kNm]
1	796.96	61.06	13.05	784.62
2	488.00	38.57	12.65	495.62
3	657.36	51.15	12.85	657.27

Table 2. Comparison of strain and bending moment values for wireless system and conventional system at mid-span

Load case	Conventional system		Wireless system	
	Measured strain [μm/m]	Computed bending moment [kNm]	Measured strain [μm/m]	Computed bending moment [kNm]
1	66.78	858.27	64.70	831.49
2	77.95	1001.79	76.71	985.90
3	73.67	946.86	70.35	904.08
4	86.54	1112.15	82.45	1059.67
5	77.19	991.98	74.73	960.39

strain and calibration factors were used to determine bending moments on the girder for dynamic loads. Parameters evaluated for the mid-span location are given in Table 2. A good agreement between the wireless system and conventional system results was established. The system deployed at the site was used for getting responses from the bridge during the passage of trains. A typical variation of the bending strain response measured via a wireless sensor during passage of a train (load case 1) is shown in Figure 11.

Figure 10. Wireless sensor node deployed at bridge site

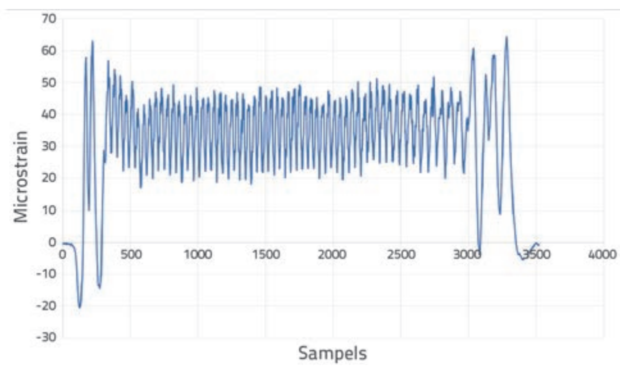

Figure 11. Typical variation of strain measured by wireless sensor during train passage

6. Conclusion

This paper briefly describes studies carried out to evaluate performance of wireless NI measurement nodes. An application was developed in LabVIEW for acquiring the real time data from measurement nodes in wireless mode. The developed application was tested in laboratory and was found to be working satisfactorily. It enables real-time plotting of measured data, as well as subsequent processing of these data. Comparison was made with the strain measured via a conventional data logger. A good correspondence was established between these strain values. After that, the wireless nodes were deployed at a railway bridge site, along with a conventional system. Responses were measured during the passage of trains and structural parameters were evaluated. It was observed that the parameters evaluated by both systems are in good agreement. Hence the system will also be adopted in similar structural health monitoring applications.

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