Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 87 (2014) 680 – 683

Procedia Engineering

www.elsevier.com/locate/procedia

EUROSENSORS 2014, the XXVIII edition of the conference series

Development and evaluation of a WSN for real-time structural health monitoring and testing

A. Depari, P. Ferrari, A. Flammini, S. Rinaldi, M. Rizzi, E. Sisinni*

Department of Information Engineering, University of Brescia, via Branze 38, Brescia (25123), Italy

Abstract

In this work, a detailed analysis of a low-cost wireless sensor network for structural health monitoring and testing is provided. Differently from other works available in literature, main goals simultaneously pursued in the design of the wireless sensor network are the scalable sampling rate, the time synchronization of measurements and the limited amount of computational and memory resources. In order to minimize power consumption, still offering a real-time behavior, a star topology has been considered. The star center also behaves as a gateway towards most popular wired and wireless communication protocols; thus, cloud computing services can be adopted for analyzing data coming from monitored sites. The proof-of-concept solution physically implemented is capable to collect data from 16 nodes simultaneously with a sampling rate in the 10 Hz range and a 1-year lifetime using conventional batteries.

Peer-review under responsibility of the scientific committee of Eurosensors 2014

Keywords: wireless sensor networks; real-time communication; low power consumption; structural health monitoring and testing;

1. Introduction

Civil structures continuously undergo severe loadings during their lifetime, which may cause serious issues about the integrity of the structures themselves. In addition, extreme events such as earthquakes and typhoons may further worsen the scenario, leading to tragic disasters, like collapses of bridges or buildings. For all these reasons, in the recent past, industrialized countries are increasing their budget for structural health monitoring and testing (SHM&T).

---

* Corresponding author. Tel.: +39-030-3715445; fax: +39-030-380014.
E-mail address: emiliano.sisinni@unibs.it

Peer-review under responsibility of the scientific committee of Eurosensors 2014
doi:10.1016/j.proeng.2014.11.622

The final goal of SHM&T is to provide a continuous monitoring of civil infrastructure conditions during their whole life span. Whenever a doubt about the infrastructure load-bearing capability arises, a comprehensive load-test has to be executed, thus potentially reducing the cost for maintenance, repair or retrofit the infrastructure itself. However, traditional SHM&T solutions are expensive. Being costly and time-consuming, in situ visual inspections are no more used, since electronic logging systems are preferred; nevertheless, the high cost for installing components, such as sensors, data loggers, computers, and connecting cables, prevents their large scale adoption. In particular, analog signals are usually employed, thus requiring coaxial wires for ensuring signal integrity. It is well-known that the installation of coaxial wires in structures is generally very expensive and labor-intensive; as an example, it was estimated that installing about 350 sensing channels on the Tsing Ma Suspension Bridge in Hong Kong exceeded USD 8 million 0. The recent advent of distributed sensing solutions based on WSNs (Wireless Sensor Networks), allowing for cable removal, is consequently an interesting opportunity to overcome the cost limitation, without sacrificing the measurement accuracy.

2. Wireless Sensor Networks for Structural Health Monitoring and Testing

The term smart wireless sensor is usually adopted to address a device having the following features: sensing capabilities; on-board computational power, on-board wireless communication interface and, typically, autonomous power source (e.g., by means of batteries). Main advantages derived from the adoption of WSNs are the increased flexibility and scalability, since new nodes can be easily added on the field according to the application requirements.

Nowadays several standard solutions are available for both consumer and industrial scenarios. A typical example of the former application is ZigBee, whereas WirelessHART and ISA100.11a are two emerging standards for process monitoring and control. Clearly, the considered scenario poses some issues that must be satisfied by the data collection and transmission solution 0. Just to mention a few: prolonged lifetime despite the battery supplying, long-distance transmission (ranging from meters for structure testing to hundreds of meters for bridges continuous monitoring), wide bandwidth due to the possible large number of nodes and the relatively high sampling frequency (e.g., 2-byte data samples collected at 100 Hz generate 12 kB of data every minute), and time synchronization (every distributed measurement system needs adequate time synchronization, in order to correctly arrange logged values; often, errors due to clock drift are larger than those imputable to noise 0). For all these reasons, there is not a unique solution for wireless SHM&T, but each field of application requires a tailored solution.

A detailed review of recent proposal for wireless SHM&T is 0.

3. The proposed approach

In this work, authors focused on non-destructive load tests of structures and individual structural elements (e.g., beams, slabs…). Such tests are performed both for assessment of the structure behavior under stress and for the refinement of theoretical finite element models. As an example, load-deformation measurements are typically collected by means of linear displacement sensors when certain load is applied. From the load-deformation curve, it is possible to estimate the maximum load that can be safely applied, i.e., to check the operational limits corresponding to the elastic behavior of the structure itself. The maximum load is reached gradually through various steps and the structures remain under the action of the maximum load for a sufficiently long period of time to ensure the complete deformation of all the elements that constitute the structure under test. Generally, water (or sand) bags and bricks are used to reproduce the uniformly distributed load; however, some researchers have recommended hydraulic jacks for rapid loading.

In the considered scenario, the civil infrastructure is instrumented by means of linear (resistive) potentiometers, as shown in Fig.1, with a desired resolution on the order of 0.1 mm and a sampling rate lower than 10 Hz.

The proposed WSN implements a star topology, the center node of which is the network coordinator that is supposed to be mains powered. The physical layer is compliant with the IEEE802.15.4 standard operating in the ISM band @ 2.4 GHz. Regarding the medium access strategy, it is based on hybrid contention-based and contention-free protocols; the former is used for acyclic data, whereas the latter is used for exchanging actual measurement data.

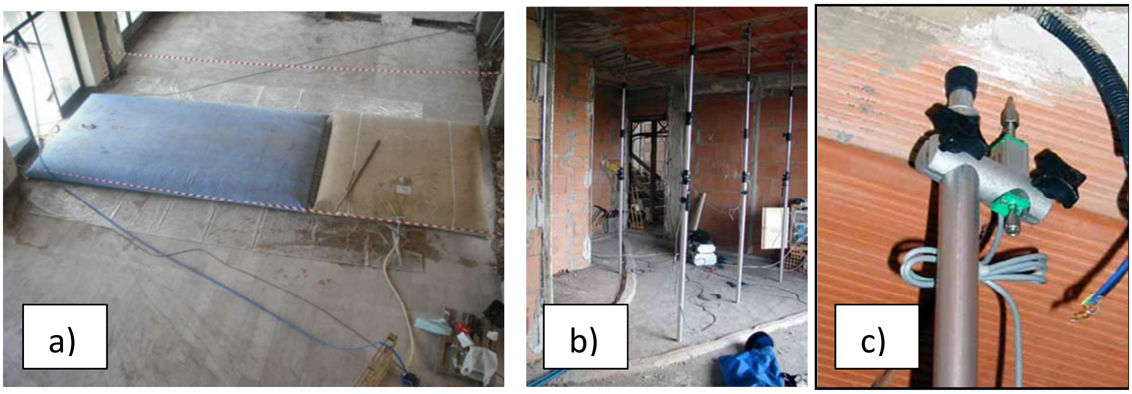


Fig.1. Example of a non-destructive load test. a) water bag for load application; b) instrumented infrastructure under test; c) detail of resistive potentiometer used for deformation measurement.

A preliminary binding phase is required for the network formation (see Fig.2), exploiting the auxiliary channel. Subsequently, measurement data are cyclically exchanged, as shown in Fig.3; acyclic communications can still occur on the auxiliary channel. Time dissemination is ensured by beacons regularly transmitted by the coordinator. The beacon payload informs the node about the actual data channel to be used next as well as the cycle duration; furthermore, it signals pending acyclic data.

The firmware (see Fig.4) implementing the previously descried proprietary protocol has been tailored to reduce memory requirements; the memory footprint is lower than 15 KB for both the coordinator and the sensor node. It must be highlighted that a MIC (Message Integrity Code) field has been inserted into every exchanged packet in order to exploit the keyed-digest mechanism for data integrity assessment.

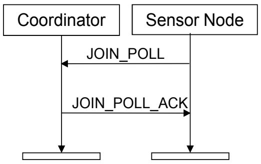


Fig.2. Binding is solicited by a node sending the Join_poll packet; the coordinator replies with the Join_poll_ack packet.

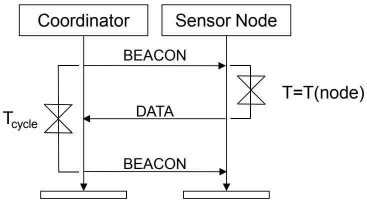


Fig.3. Measurement data is sent cyclically. A new cycle is started by a Beacon packet, which is also used for time synchronization.

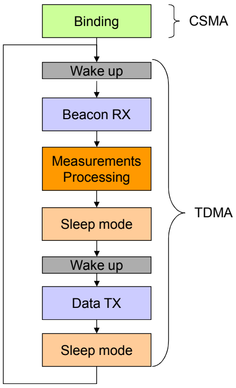


Fig.4. Block diagram of the sensor node firmware

4. Experimental results

A proof-of-concept prototype has been realized (embedding the HCS08GT60 microcontroller and the MC13192 transceiver, both from Freescale). Tests have been executed to ensure that internal ADC is effective to obtain the desired resolution (Table I). In order to minimize power consumption, several raw measurements are processed to compute a single readout (Fig.5). The node aims to minimize standby current and raw measurement duration, as shown by Fig.6. When a 500 ms cycle time is considered and 8 consecutive measurements are averaged to compute a single output, the average current consumption is I_{AVG} = 325 μA; if a 3 Ah battery is used, the expected lifetime is thus one year.

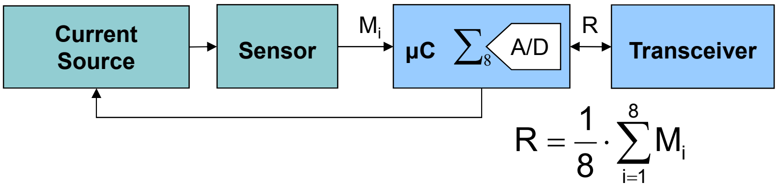
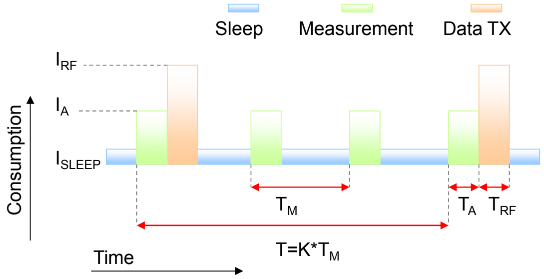


Fig.5. The implemented prototype averages 8 raw measurements in order to produce one single readout; in this way, the overall power consumption can be minimized.



$$I_{AVG} = \frac{K \cdot T_A \cdot I_A}{T} + \frac{T_{RF} \cdot I_{RF}}{T} + \frac{(T - K \cdot T_A - T_{RF}) \cdot I_{SLEEP}}{T}$$

$$\approx I_{SLEEP} + \frac{T_A}{T_M} I_A$$

Fig.6. Simplified current consumption model when filtered data obtained from K raw measurements is actually sent over the air once per cycle time T (I_A: current needed to perform single measurement lasting T_A and repeated every T_M; I_{RF}: current needed to transmit/receive data for T_{RF}; I_{SLEEP}: low-power mode current consumption lasting $T - K \cdot T_A - T_{RF}$).

Tab.1. Microcontroller internal ADC characterization (coherent sampling is adopted).

Input signal amplitude (sine, mVpp)	ENOB	Nominal resolution
3000.0	9.3	10
1500.0	8.4	09
0750.0	7.4	08
0375.0	6.3	07
0187.5	5.4	06

References

[1] S. Cho, C-B. Yun, J. P. Lynch, A. T. Zimmerman, B. F. Spencer, T. Nagayama, Smart Wireless Sensor Technology for Structural Health Monitoring of Civil Structures, Steel Structures, 8 (2008) 267-275.
[2] T. Nagayama, S. H. Sim, Y. Miyamori, B. F. Spencer Jr., Issues in structural health monitoring employing smart sensors, Smart Structures and Systems, 3 (2007) 299–329.
[3] V. Krishnamurthy, K. Fowler, E. Sazonov, The effect of time synchronization of wireless sensors on the modal analysis of structures, Smart Materials and Structures, 17 (2008) 1-13.
[4] Guang-Dong Zhou, Ting-Hua Yi, Recent Developments on Wireless Sensor Networks Technology for Bridge Health Monitoring, Mathematical Problems in Engineering, (2013) 1-33.