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Technical Report

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HURRAY-TR-100909

Version:

Date: 09-09-2010

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Abstract

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A Wireless Sensor Network Platform for Structural Health Monitoring: enabling accurate and synchronized measurements through COTS+custom-based design

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Abstract: Structural health monitoring has long been identified as a prominent application of Wireless Sensor Networks (WSNs), as traditional wired-based solutions present some inherent limitations such as installation/maintenance cost, scalability and visual impact. Nevertheless, there is a lack of ready-to-use and off-the-shelf WSN technologies that are able to fulfill some most demanding requirements of these applications, which can span from critical physical infrastructures (e.g. bridges, tunnels, mines, energy grid) to historical buildings or even industrial machinery and vehicles. Low-power and low-cost yet extremely sensitive and accurate accelerometer and signal acquisition hardware and stringent time synchronization of all sensors data are just examples of the requirements imposed by most of these applications. This paper presents a prototype system for health monitoring of civil engineering structures that has been jointly conceived by a team of civil, and electrical and computer engineers. It merges the benefits of standard and off-the-shelf (COTS) hardware and communication technologies with a minimum set of custom-designed signal acquisition hardware that is mandatory to fulfill all application requirements.

1. INTRODUCTION

Structural Health Monitoring (SHM) and damage identification at the earliest possible stage have been receiving increasing attention from the scientific community and public authorities. Damage identification is relevant to all engineering fields as service loads and accidental actions may cause damage to the structural systems (Pines *et al.*, 1997).

Conventional monitoring systems used for these applications in civil engineering studies involve large number of wires (copper or fibber-optic cables) and centralized data acquisition systems with remote connections. As damage is a local phenomenon and in order to achieve high accuracy, it is important to monitor the structural behaviour at fine-grained level. Thus, a sufficiently large number of measuring points is necessary. The fact that the conventional sensor platforms use wires increases the cost of the monitoring systems and creates difficulties in their maintenance and deployment.

Adding to the fact that the cost of traditional wire-based monitoring systems is driven by the number of sensors, the installation time and installation costs limit the scale of deployment of such systems (Lynch *et al.*, 2006). From experience, the installation time of a structural monitoring system for bridges and buildings can consume over 75% of the total testing time, and the installation labour costs can approach well over 25% of the total system cost (Lynch *et al.*, 2000). These installation time and device costs can be greatly reduced via Micro-Electro-Mechanical Systems (MEMS) based sensors integrated in Wireless Sensors Networks (WSN). In this line, the recent years have witnessed an increasing interest in a new technology based on WSN platforms as a low-cost alternative for being applied in civil engineering structures (Lynch *et al.*, 2006).

Previous work from the same team (collaboration between the CISTER and the ISISE research units) focused on a SHM system strictly based on commercial off-the-shelf (COTS) technologies. This enabled a preliminarily demonstration of the applicability of MEMS+WSN-based systems for operational modal analysis of structures (Aguilar et al., 2010). Such work allowed identifying three major limitations: (1) the lack of enough sensitivity of the acceleration sensors, (2) low resolution of the Analogue-to-Digital Converter (ADC) embedded in the WSN platform, and (3) the lack of synchronization algorithms.

The SHM system illustrated in this paper solves the limitations from our previous work and blends both the advantages of using COTS and customized hardware and software technologies. Importantly, the proposed system architecture aims not only to respond to the application scenario under consideration – operational modal analysis of Civil Engineering structures– but also to other types of applications where mechanical constructions (e.g. industrial machinery, vehicles) under stress (natural or induced) require structural integrity monitoring and/or analysis.

The remainder of this paper is structured as follows. Section 2 presents some related work in this area. Section 3 provides a system overview, emphasising the underlying application requirements. Section 4 details the WSN architecture and related implementation aspects. The hardware platform, with particular emphasis on the signal acquisition board, is described in Section 5. In Section 6, a comprehensive explanation of the application interface with the WSN and the application scenario is presented, together with a discussion on the results of the tests carried out to validate the prototype platform. Finally, Section 7 draws some conclusions and outlines future work.

2. STATE OF THE ART

SHM has been a very active research area among both academics and industrialists, especially in what concerns recent developments in WSN and Micro Electromechanical Systems (MEMS) (Lynch *et al.*, 2006).

Nevertheless, existing solutions for SHM using WSNs present one or more of the following limitations: a) low sampling resolution (typically 8-12 bits systems, which invalidates SHM based on operational modal analysis); b) no explicit synchronization mechanisms between sensing nodes; c) not relying on standard communications protocols (commonly they use IEEE 802.15.4-compliant devices that neither implement the IEEE 802.15.4 medium access control (MAC) nor ZigBee protocols); d) not building upon *de facto* operating systems (OS) for WSNs platforms (e.g. TinyOS, Contiki); e) not relying on COTS technologies (more cost-effective). Examples of relevant work follow, highlighting some of their limitations.

The system proposed by Xu *et al.*, 2004, which was re-evaluated by Paek *et al.*, 2005, despite using a reasonable sampling resolution (16 bits), lacks an explicit synchronization mechanism between the sensing devices. The implementation provides *a posteriori* time correlation of the samples, which is not satisfactory for some operational modal analysis algorithms that require that samples from all sensors are acquired simultaneously.

Researchers at WSU-SL (e.g. G. Hackmann et. Al) proposed a system based on iMote2 platforms, which may present some system lifetime limitations due to their energy consumption. Additionally, no strict sensor data synchronization is supported (forcing to correlate data *a posteriori*) and validation was just based on external stimulus (not addressing the natural vibration) or on simulation.

Whelan *et al.*, 2009 described an innovative system composed of twenty sensing nodes deployment in a highway bridge. Nevertheless, the system uses a non-standard communication stack, and the WSN platform microprocessor does not run a known OS. Additionally, they provide no detail on the synchronization mechanism.

Ceriotti *et al.*, 2009 presented a very complete implementation of a SHM application that allows monitoring several phenomenon of interest when monitoring heritage buildings (accelerations, deformation and environmental parameters). However, the particularities of the system and its inherent customization level limit its application to a narrow type of structures. Moreover, the synchronization mechanism is based on a custom middleware, and takes few advantages of the native functionalities of the communication protocol, requiring a constant refreshment and storage of temporal information in order to maintain time-consistency.

3. SYSTEM OVERVIEW

3.1 System Requirements

The aim of the system is to sample in a synchronized fashion multiple accelerometers placed at different locations in a structure and forward the data to a central station for later processing. The most relevant application requirements were identified as follows:

- XYZ accelerometer (triaxial)
- Max. measurement range: ± 1 g
- Minimum sensitivity: 1 V/g
- Typical resolution: 1 mg
- Max. resolution: 50 µg
- Frequency response, 3 dB: 0 - 100 Hz
- Max. sampling rate: 100 Hz
- Max. sampling drift between sensors : 10 ms
- ADC resolution: 24 bits
- 0% sample lost during sampling process

Ensuring the correct synchronization of the sensing operation is of major importance for this kind of monitoring applications (Xu *et al.*, 2004; Lynch *et al.*, 2006; Cinque *et al.*, 2006; Whelan *et al.*, 2009). This means that samples from all sensors must be acquired in a synchronized way in order for the data analysis algorithms to provide consistent results.

3.2 Snapshot of the System Architecture

The system architecture was designed in order to satisfy the identified application requirements and is illustrated in Fig. 1, considering a prototype system composed by four Sensing Nodes. Each Sensing Node is composed by a TelosB node (Crossbow, 2009) with a signal acquisition board (SAB) attached to a MEMS acceleration sensor (see Section 5).

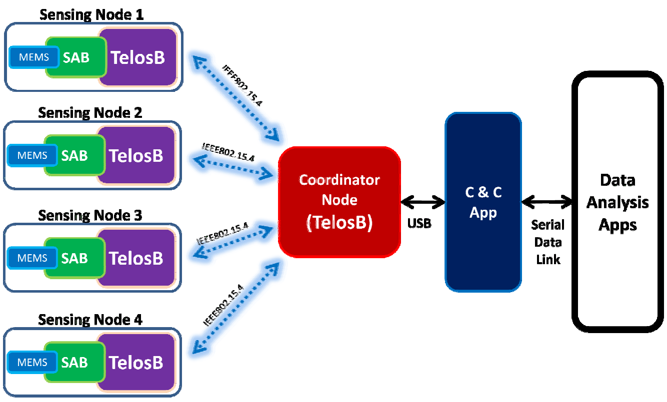


Fig. 1. Snapshot of the System Architecture

All four Sensing Nodes communicate with a Coordinator Node (also a TelosB node) via a standard communication protocol (IEEE 802.15.4). The Coordinator Node supervises the network and nodes activities (e.g. node configuration, start/stop sampling) and guarantees a tight synchronization between all nodes; it also forwards the configuration parameters and dispatches the acquired data to the Command & Configuration Application (C&C App). The WSN architecture is described in Section 4.

The Command and Configuration application (C&C App, briefly described in Section 6.1) provides the system user with a human-machine interface (HMI) to configure the system and also an application programming interface (API) to integrate the WSN system with the data processing/analysis applications. The latter enable to infer about the reaction of the monitored structure to natural vibration or impacts, as outlined in Section 6.2.

4. WSN ARCHITECTURE

As previously stated, the proposed SHM system aims at sampling several accelerometers placed at different locations in a structure, in a synchronized fashion. Sampled data is to be stored in each Sensing Node until it is retrieved by a central node for processing. To enable the analysis of the results, namely the modal shape analysis, it is crucial to guarantee the temporal correctness of the system.

4.1 Guaranteeing Synchronization

According to Cinque *et al.*, 2006, the maximum drift between samples should be computed as presented in (1):

$$\left|C(s_i) - C(s_j)\right| \leq \frac{1}{f_s} \forall i = 1 \dots N \neq j \qquad (1)$$

where $C(s_i)$ is the clock of the i-th sensor, N is the total number of sensors and f_s is the sampling frequency.

The existing timers in the TelosB platform depend on a 32.768 Hz Citizen CMR200T quartz crystal (Citizen, 2006). This crystal features a drift of ±20 ppm in relation to its nominal frequency. This means that (in the worst-case) there is a drift of approximately 20 µs at every second.

Assuming a sampling frequency of 100 Hz results in a sampling period of 10 ms. For keeping the drift bellow 10 ms, according to the application requirements, it will be necessary to synchronize every 500 s at most. This result imposes the existence of a synchronization mechanism in the WSN, so that all nodes have the same time reference.

There already exist some mechanisms to achieve synchronization in wireless networks. The simplest approach is to use the Global Positioning System (GPS) as the source for a universal clock. GPS can provide extremely accurate timing, but requires special (typically power hungry) receivers and a clear sky view.

Many of the proposed protocols solve the synchronization problem by transmitting in-band synchronization information. Typically, these involve creating some form of hierarchical organization and use it to distribute timing information. There are several in-band time synchronization schemes in the literature, where some providing good accuracy are RBS (Elson *et al.*, 2002), TPSN (Ganeriwal *et al.*, 2003) or FTSP (Maroti *et al.*, 2004). Notably, the work from Werner-Allen *et al.*, 2005, is the only practical synchronization strategy that does not require nodes to construct a hierarchical organization, but it can take an unbounded number of broadcasts to achieve synchronization. Another approach to this problem is RT-Link (Rowe *et al.*, 2006), a TDMA-like protocol that can use an out-of-band synchronization mechanism, avoiding in-band solutions that reduce network performance.

The IEEE 802.15.4 protocol provides a standard-based solution for synchronization (beacon-enabled operation mode) that fits the application requirements (Section 3.1). Thus, it has been selected for the WSN communication infrastructure. A Coordinator node (officially named PAN – Personal Area Network – Coordinator) schedules channel access and data transmissions in a messaging structure – the Superframe. This node is also responsible for periodically transmitting a beacon frame announcing the start of the Superframe (IEEE 802.15 TG4, 2010). Upon beacon reception, each Sensing Node triggers an external GPIO (General Purpose Input/Output) pin on its Signal Acquisition Board (SAB) in order to synchronize it.

4.2 Communication Architecture

The prototype system consists of five TelosB (Fig. 1) nodes. These hardware platforms feature a TI MSP430 16-bit microcontroller, a CC2420 RF transceiver (IEEE 802.15.4-compliant), 48 kB of Program memory (in-system reprogrammable flash), 10 kB of EEPROM, two UART communication ports, and I2C. They also include in-board light, temperature and humidity sensors, which might be useful for some SHM application scenarios.

Four nodes act as Sensing Nodes and control the corresponding SABs, while one node acts as the Coordinator Node, assuming network management (including network configuration and synchronization), data collection and interfacing with the Command and Configuration application (C&C App). Implementation of the Sensing and Coordinator Nodes software was done in nesC (Gay *et al.*, 2003) over the TinyOS operating system (TinyOS, 2010). The open-ZB implementation of the IEEE 802.15.4 protocol has been used (MASS, 2007; Open-ZB, 2010).

Fig. 2 presents a message sequence chart of the application:

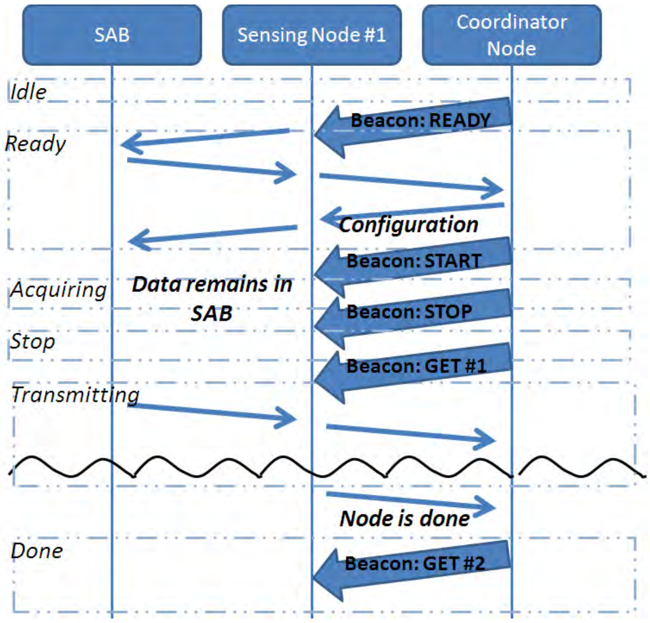


Fig. 2. Message sequence chart

The WSN application commutes between 6 states, as follows:

(1) *Idle* - As soon as the nodes are powered they enter the *Idle* state. At this stage, the open-ZB IEEE 802.15.4 stack is initiated and the nodes try to synchronize and associate with a PAN Coordinator. The Channel Scan feature of the protocol stack is disabled, since the network topology is fixed.

(2) *Ready* - As soon as every node is synchronized, the user signals the Coordinator to initiate the *Ready* state. This is done by changing the information in the IEEE 802.15.4 beacon payload. Each Sensing node receives the beacon,

parses the payload information and immediately checks the presence of a SAB. The Coordinator is then signalled by each node concerning its readiness. Upon the reception of this message, the Coordinator informs the C&C App about the state of each node.

(3) *Acquiring* - When every node is configured, the user can start the signal acquisition process by sending a command to the Coordinator that will signal the Sensing Nodes for start sampling, through a beacon frame. All Sensing Nodes trigger the SABs and re-synchronize them at every beacon.

(4) *Stopped* - The user sends a command to the Coordinator to stop the data acquisition process. Again, the Coordinator signals the network using its beacon at the beginning of the next Superframe. All the nodes stop the data acquisition process when the beacon embedding this command is received. The sampled data is stored in the SABs memory until the respective node is polled by the Coordinator.

(5) *Transmitting* - After signalling the *Stop* state for the network, the Coordinator initiates the *Transmitting* state by pooling a Sensing Node at a time for data. Every message payload embeds 8 samples which are relayed to the C&C App, upon reception by the Coordinator.

(6) *Done* - All Sensing Nodes signal the Coordinator upon completion of the *Transmit* state. When the last Sensing Node informs the Coordinator that there is no more data to send, the Coordinator enters the *Done* state.

4.3 Coordinator node

The Coordinator node is responsible for synchronizing the network and managing the application. It also serves as a sink to the sampled data sent by the Sensing Nodes. Such data is immediately forwarded to the C&C App without any processing, for later analysis.

The Coordinator supports two types of commands: (1) **Board Commands** – used to configure the SABs; these commands are transmitted to the corresponding node, and then directly forwarded to the SAB, using regular IEEE 802.15.4 data frames; (2) **Network Commands** – used to manage the monitoring application.

There are two kinds of commands within the former category: (a) Node Management commands; (b) Application Management commands. The Node Management commands are sent to the Sensing Nodes using regular IEEE 802.15.4 data frames during the application *Ready* state. These include setting the behaviour of the node (active/passive), remote reset, channel selection, and requesting onboard sensor reading (temperature and humidity). The Application Management commands are sent within the payload of the IEEE 802.15.4 beacon frames (Fig. 2) so that all nodes receive and process the command at the same time, thus guaranteeing synchronization (there is no contention in beacon transmission).

The commands are described as follows: (1) IDLE, This command indicates that the system is in *Idle* state, waiting for input from the User; (2) READY - It marks the beginning of the configuration phase for the nodes. When receiving this command, the Sensing Nodes wait for a configuration packet from the Coordinator, including sampling rate, period and time. They also wait for a message to set their behaviour as active or passive. (3) START – This command triggers the beginning of the signal acquisition from the accelerometers. The SABs are synchronized at each beacon and save the samples in its internal memory. (4) STOP – Upon reception of this command, Sensing Nodes stop the data acquisition procedure (command sent to the SABs) and wait for further instructions. (5) GET <address> - The Coordinator polls each Sensing node with the GET command, to trigger the transmission of the sample data stored at the Sensing Nodes SABs memory. Each Sensing Node checks the address embedded in the beacon payload. (6) RESET – This command signals the end of an acquisition cycle. After receiving this command, a Sensing Node switches to the *Ready* state.

All commands are acknowledged by the Coordinator upon reception at the UART (sent by the C&C App).

4.4 Sensing Nodes

The Sensing Nodes (Fig. 3) control and synchronize the acquisition of the SABs, and carry out the acquisition of the embedded sensors measurements (temperature, humidity, voltage, luminosity).

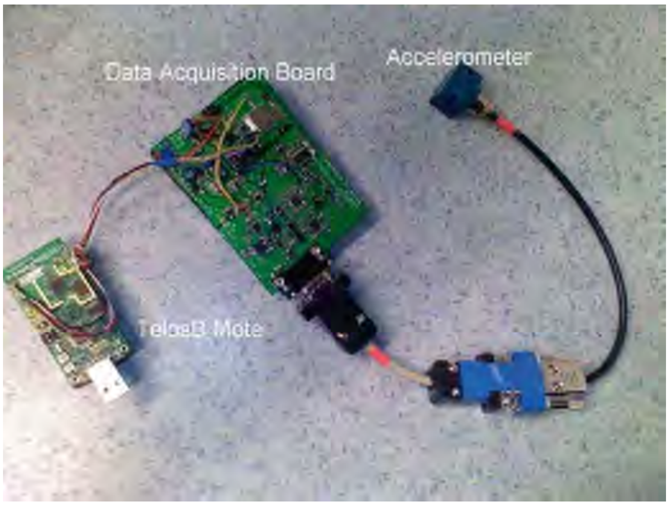


Fig. 3. Sensing Node, SAB and accelerometer

The architecture of a Sensing Node is illustrated in Fig. 4. All the application as well as the open-ZB stack was developed in nesC, over TinyOS. Communications with the SAB are handled using the UART serial interface of the TelosB. Two additional general purpose input/output (GPIO) pins of the TelosB are used to enable the synchronization of the SAB and to control the communication flow.

At the beginning of the application, the Coordinator's beacon is set to IDLE. Upon application input, the Coordinator changes payload to READY signalling all boards. When the Sensing Node is informed of the beginning of the *Ready* state, it will immediately check for the presence of the SAB using its UART interface. If the SAB responds, the Sensing Node signals the Coordinator that everything is ready. Otherwise it will signal the error using an Error Message with the respective error code. Sensing Nodes are then activated and configured by the Coordinator.

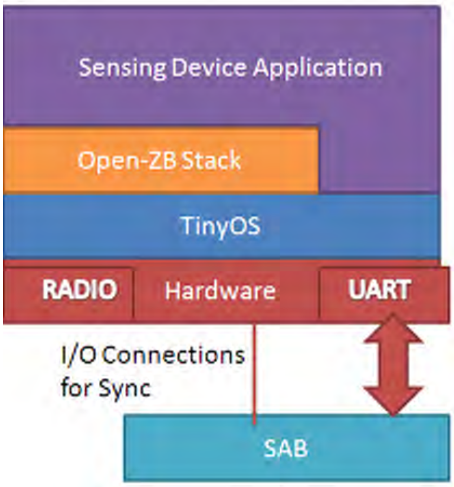


Fig. 4. Architecture of a Sensing Node

Sampling is started by sending the START command in the beacon payload. When the sampling time expires, the Coordinator changes its beacon payload to send the STOP command. Upon reception of the GET command, the Sensing Nodes initiate the transmission of the sampled data stored at the SAB to the Coordinator Node. Finally, the Sensing Nodes signal the Coordinator that the data transmission is over.

5. SIGNAL ACQUISITION SUB-SYSTEM

A custom-designed signal acquisition board (SAB) had to be conceived for supporting: a) a high resolution 24-bit ADC; b) enough memory for storing data samples.

MEMS sensors are quite appealing for WSN applications, due to their low energy consumption, low voltage operation, small size and low cost. Although there are several MEMS sensors in the market capable of satisfying the requirements outlined in Sub-Section 3.1, complete ready-to-use COTS devices are still scarce.

Some of the most suitable devices for these applications are commercialize by Advanced Sensors Calibration (ASC, Germany), Crossbow (USA) and Silicon Designs Inc. (USA). Among the referred manufactures' portfolios, the triaxial accelerometer model ASC 5631-002 (Advanced Sensors Calibration, 2009) was identified as an interesting solution (characteristics outlined in Table 1):

Table 1 – ASC 5631-002 characteristics

Range	±2 g
Sensitivity	1 V/g
Frequency	100 Hz ±3 dB
Linearity	±1.0 % FSO
Signal output	500 mV to 4500 mV (DC)
Zero output	2500 mV ±100 mV
Supply voltage	5 V ±0.1 V
Current consumption	7 mA (max.)
Cost	250 Eur + VAT

Fig. 5 depicts the overall architecture of the SAB. A common energy source (e.g. battery) supplies the COTS WSN platform and the SAB hardware. The system voltages are then derived from this energy source. Note that both the WSN platform and the SAB's digital section voltage regulator are independent of the remaining system voltages. This arrangement allowed switching on/off all the onboard analogue circuitry, which enables a substantial improvement in the overall energy consumption.

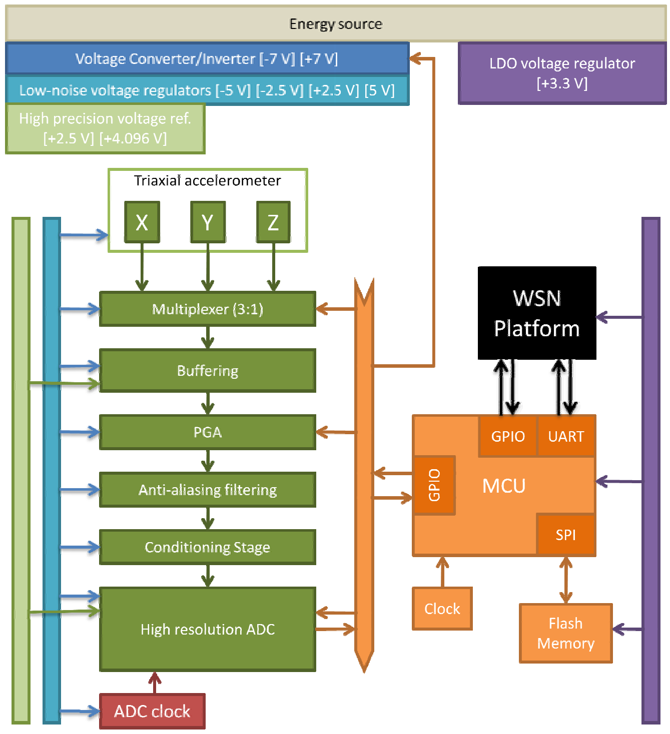


Fig. 5. Sensor Acquisition Board (SAB) architecture

In this particular case, the outputs of the Triaxial accelerometer are multiplexed by a 3:1 multiplexer. The selected analogue signal then crosses the initial buffering and programmable gain stages. Then, an analogue 8th order Butterworth filter limits the signal's maximum frequency to 100 Hz to avoid undesired aliasing effects. Then, the filtered signal goes through a final conditioning stage and enters into a high-resolution 24 bits ADC.

The digital circuitry connections (arrows connected to the microcontroller - MCU) represent its relation towards the MCU internal architecture, as briefly described next.

The MCU is responsible for controlling all the SAB hardware, which includes the procedures for proper ADC behaviour, handling the samples storage until WSN platform request and additional samples pre-formatting.

Note that the voltage converter/inverter (that supplies the analogue circuitry) is directly connected to the MCU (enabling on/off control). The input multiplexer, the programmable gain amplifier (PGA) and the high resolution ADC are connected to the MCU by several GPIO lines.

The data transmission from the MCU to the flash memory is achieved through the serial peripheral interface (SPI) bus. The MCU connects with the WSN platform by its internal UART hardware and a couple of two GPIO lines.

6. TEST AND VALIDATION

This section describes how the proposed SHM system (and the underlying architecture) was tested and validated in a real application scenario.

6.1 Command and Configuration Application

In order to provide the necessary HMI and API for the data analysis applications, a Command and Configuration Application (C&C App) was developed (Fig. 6).

Fig. 6. Command & Configuration Application

The available controls of the C&C App enable full control over the acquisition configuration parameters (i.e. axis selection, sampling rate, sampling period, sampling duty cycle, etc.) and also provides a quick evaluation of the presence of the system nodes. Several additional features are also built-in to assist the user with relevant information on the network and acquisition parameters configuration.

One additional goal of the C&C App was to provide a convenient interface between the WSN and the data processing/analysis application. The implemented mechanism allows a transparent interface with the system, in a very similar with the previously used, which are typically serial data interfaces.

To complete the data acquisition process, a VI routine was developed in Labview (Labview, 2006) for the interpretation and conversion into standard units, for receiving the messages from the serial port as well as their local storage in the central station.

6.2 Experimental Modal Identification Tests

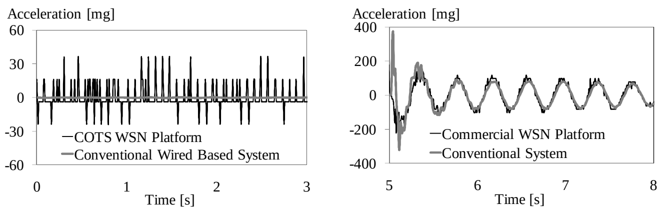
A single degree of freedom structure represented by an inverted pendulum is one of the simplest examples used by the civil engineers to explain the fundamentals of the dynamics of structures. In this work, this structure was also used as a tool to evaluate and understand the behaviour of the COTS WSN and the developed prototype for operational modal analysis of civil engineering structures.

As it is shown in Fig. 7, the studied specimen consists in an inverted wooden pendulum with 1.70 m height built specially for testing purposes in the civil engineering laboratory at the University of Minho. The pendulum was designed in such a way that its dynamic properties replicates the properties of the Mogadouro´s Clock Tower, an old masonry tower in the northern part of Portugal, which was previously studied and presented in Ramos (2007).

For comparison purposes, both WSN platforms were evaluated considering as references conventional wired based systems which consist in high sensitivity piezoelectric accelerometers model PCB 393B12 (PCB, 2009) as well as the NI-USB9233 (NI, 2009) as data acquisition board.

Fig. 7. Laboratory system idealization/experimental setups

The initial tests were meant to observe the performance of the COTS technology on WSN platforms for dynamic monitoring studies. With this purpose, the accuracy of the time series recordings of these platforms (MICA2 solution + MTS400 board) was evaluated using only one of the conventional accelerometers and mote placed at the top of the Pendulum. The results of these tests are presented in Fig. 8.



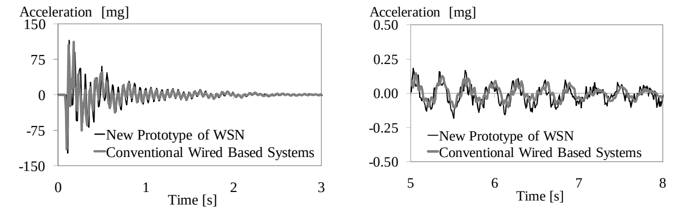
(a) (b)

Fig. 8. Time domain series recorded using COTS WSN platforms: (a) low amplitude excitation recordings; and (b) higher amplitude excitation recordings

The results of the first test indicated the good performance of the commercial WSN platforms for measuring high amplitude vibrations. As it was expected, for signals with amplitudes below 20 mg, the WSN platforms recorded only noise (it is even feasible to observe the digitalizing lines) due to the low resolution of the micro-accelerometers and the ADC_s embedded. However, it is important to state that in SHM studies of civil engineering structures, vibrations with amplitudes below 2 mg are commonly found. Moderate differences (less than 5%) were found in the frequencies detected with both systems (wired and COTS WSN) as well as meaningless results for the mode shape detection task due to the lack of the implementation of synchronization algorithms in the commercial WSN platforms.

Using the developed prototype of WSN platform, a second round of tests were carried out considering the same inverted pendulum as case study.

The first test was aimed to observe the quality of the time series recordings of the developed platforms. With this purpose, the effect of an impulse force was registered using one conventional accelerometer and one new sensing node, both located at the top of the pendulum. The tests were carried out considering a sampling rate of 100 Hz and sampling time of 10 s. The results are shown in Fig. 9.



(a) (b)

Fig. 9. Time domain series recorded using the developed prototype of WSN platform: (a) High amplitude excitation recordings; and (b) lower amplitude excitation recordings

As it was shown, even for signals with amplitudes below than 0.25 mg, the records from the new developed WSN platform and the conventional wired based accelerometers presented a remarkable degree of similarity.

The subsequently stage consisted on the verification of the accuracy of the frequency content of the acquired signals with the developed WSN platforms. Considering the same pair of sensors located at the top of the pendulum and 30 s of sampling time, experiments in two excitation scenarios were carried out: random impacts tests (vibrations with amplitudes below 5 mg) and ambient noise tests (vibrations with amplitudes below 1.5 mg). The Welch Spectrums (Welch, 1967) of the time series records were calculated and are presented in Fig. 10.

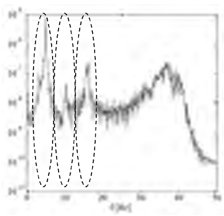
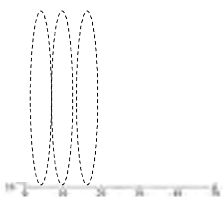
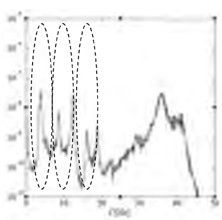
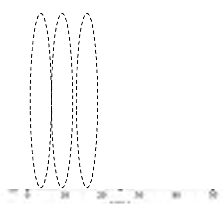
	Conventional Systems	New Prototype of WSN
Excited Tests		
Ambient Tests		

Fig. 10.Frequency domain results – Tests new WSN Platform

The results evidenced the high accuracy of the resultant frequency domain spectrums calculated from the records of the new developed system. With this respect, even in the case of ambient noise tests, outstanding similarities in the content of frequencies were detected.

The last stage of the experimental operational modal analysis process consists on the estimation of the dynamic properties of the structures by means of their natural frequencies, damping coefficients and mode shapes.

For this purpose, a more refined data processing method was used which consisted on the evaluation of the time series recordings with 3 conventional and new developed sensors located at the top of the pendulum using parametric time domain techniques such as the Stochastic Subspace Identification (SSI) method (Van Overschee; and De Moor, 1991). Fig 11 shows the results of this analysis only for the case of random excited system.

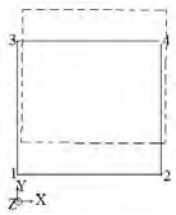
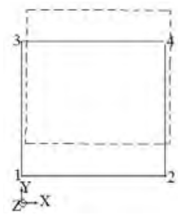
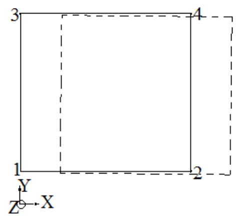
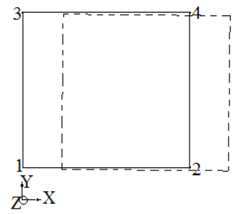
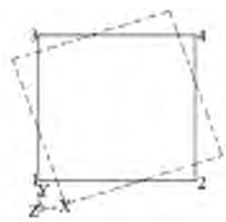
	Conventional Systems	New Prototype of WSN
1st Mode Shape		
2nd Mode Shape		
3rd Mode Shape		

Fig. 11. Experimental modal analysis results under excited environment – Tests new WSN Platform

The first two mode shapes of the structure were identified with no uncertainties. However, there was registered a light difference in the 3rd mode shape which will be further investigated in future stages of the present research project.

Table 2 summarizes the results of the experimental modal identification studies performed in the pendulum using the conventional wired based systems and new WSN platforms.

Table 2 – Modal Identification Results

	Conv. Systems		**New Prototype of WSN**		**Error**	
Mode	f (Hz)	ξ (%)	f (Hz)	ξ (%)	Δf(%)	Δξ(%)
1	3.26	2.0	3.34	2.4	2.5	20.0
2	5.00	2.3	4.94	1.9	1.2	17.4
3	16.07	1.2	16.03	2.0	0.3	66.7

7. CONCLUSIONS

This paper describes a wireless sensor network (WSN) system for monitoring physical infrastructures. Building upon the cons of traditional wired-based solutions, several solutions based on WSNs have been proposed, but there was a lack of ready-to-use and off-the-shelf WSN technologies able to fulfil some more demanding requirements of these applications (e.g. monitoring bridges, historical buildings or vehicles structures).

This paper describes a solution that is mostly based on standard and off-the-shelf technologies, namely in what concerns hardware platforms, operating system and communication protocol. Only a minimum set of custom-designed signal acquisition hardware was conceived, in order to serve as an interface between the accelerometers and the sensing nodes. Our solution is low-power and low-cost and guarantees accurate and time synchronized measurements.

Future work will focus on extending the WSN architecture proposed in this paper in order to support a higher number of nodes and a wider region under monitoring, still guaranteeing a tight synchronization between all nodes.

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