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“A LOW COST MULTI-SENSOR SYSTEM FOR INVESTIGATING THE STRUCTURAL RESPONSE OF BUILDINGS”

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ABSTRACT

Early Warning Systems (EWSs) for the monitoring of buildings and structures are strategic to implement efficient safety actions. Even if very accurate monitoring solutions are available in the market, these are not suitable for the distributed monitoring of large areas due to costs, maintenance and installation needs.

In this paper a low cost approach to investigate the seismic response of buildings is presented. The proposed architecture is based on a customized network of multi-sensor nodes, equipped with two inclinometers and one triaxial accelerometer. The sensing system is aimed to detect accelerations and tilt angles with a resolution of about 0.02 g (0.2 m/s^2) and 0.004°, respectively, in the frequency range of (0.5 - 10) Hz. Each multi-sensor node is also equipped with a 16 bit Analog-to-Digital Converter, a micro SD card writer and a rechargeable battery. Performances of the developed multi-sensor node have been deeply investigated by means of a vibrational system. The response of the multi-sensor node to a real seismic stimulation and the comparison with a commercial device will be discussed. Experimental surveys in real sites will be also presented. Two operating modes have been implemented to make the system context-adaptive: continuous data transfer and event triggered. A wireless connection has been exploited to communicate with a remote server. Moreover, a dedicated Wavelet based paradigm has been developed to highlight structural response to seismic sources from other exogenous inertial components. Results obtained during different experimental surveys demonstrate the suitability of the developed system, which open the possibility to develop a low cost early warning approach for the structural monitoring.

1. INTRODUCTION

An Early Warning System (EWS) can be defined as a multifunctional system including sensors, signal processing and communication facilities aimed for putting actions to minimize the impact of the incoming hazard [Farrar et al., 2007]. The large number of seismic areas pushes toward the development of innovative solutions to implement reliable and low cost EWSs for the structural monitoring. Factors which could compromise the health status of buildings, producing issues related to a rational and objective performances assessment of structural and non-structural components, are analyzed in [Fabbrocino and Rainieri, 2012]. Seismic events are among major causes of structural damage and failure while representing a serious risk for the population.

Discrete measurements are often performed to assess the health status of structures (Structural Health Monitoring - SHM), while signal processing are used to extract damage-sensitive features from these measurements [Brownjohn, 2007]. Standard solutions for structural monitoring are very accurate, while providing spare information over the time with a poor spatial resolution [Feng et al., 2010]. Moreover, such approaches are expensive and high demanding in terms of installation and power consumption. The latter is a critical issue, especially when a battery operation is required. The availability of reliable, low cost and continuously running EWSs for the early detection of structural failures would be strategic, especially for high risk environments like schools or public buildings and structures (i.e. bridges). The importance of EWSs in structural monitoring is related to the possibility to timely measure anomalous deformations and/or solicitation responses which could highlights structural integrity issues.

Examples of EWSs for structural health monitoring are available in the literature. In [Waidyanatha, 2010], authors proposed a framework for synergy between SHM and Earthquake Early Warning (EEW) for the enhanced seismic protection of a target structure. By dividing the framework into two parts, pre-event and post-event, authors developed an approach which uses EEW data as prior information to potentially reduce the prediction uncertainty in the SHM system.

In [Wu and Beck, 2012], an effective SHM system has been designed. It is based on integration of several sensors and hardware components in a modular architecture. In this case, efforts have been made to reduce the volume of data to be transmitted, a key aspect for reliability and sustainability of infrastructure, in particular when several constructions are monitored at the same time by a single master node [Wu and Beck, 2012]. In [Rainieri et al., 2008] a landslide case history has been presented which describes an automated monitoring system, using inclinometers to track ongoing creep movements and providing early warning alerts [Myers et al., 2000]. Examples of networks for the monitoring of the integrity of bridges are shown in [Machan and Bennett, 2008] and [Fraser et al., 2010].

The concept of distributed EWSs has significantly increased with the availability of wireless sensor networks (WSNs) based on embedded architectures and Micro-Electro-Mechanical-Systems (MEMS), which overcome problems related to wirings and reduce the overall costs [Andò et al., 2011]. A multi-faceted network-based investigation for SHM, implementing an optimized strategy for damage detection in large structures, is provided in [Caffrey et al., 2004]. Examples of low cost SHM systems for bridges, buildings and structures based on wireless transmission systems and MEMS devices are shown in [Tan et al., 2011; Kumar and Bajpai, 2012; Ha et al., 2013]. A survey on wireless systems for the health monitoring of large structures is presented in [Wang and Liao, 2006]. Despite above examples, the use of distributed EWSs for the structural monitoring of domestic buildings is not so widespread, probably due to high costs and very demanding installation. Moreover, efficient EWSs for structural monitoring require a suitable signal processing and data mining guaranteeing the fast and reliable generation of alert notifications [Cantore et al., 2007; Li et al., 2004; Ko and Ni, 2005].

This paper draws an overview of a research activity aimed to design and validate a low cost multi-sensor node, with embedded signal processing facilities, to investigate the seismic response of buildings [Andò et al., 2014a; Andò et al., 2014b; Andò et al., 2015].

The idea behind the proposed solution is the possibility of implementing a structural monitoring strategy which exploits continuously running multi-sensor nodes, which are able to provide a real time status of the structure with a high spatial resolution [Andò et al., 2015], and a dedicated signal processing.

Advantages of the developed system reside in the easy of use, low cost, the multi-sensor approach, adaptive data transfer operating modes as well as specific features provided by the developed advanced signal processing. Actually, in order to discriminate the structural response to seismic sources from other exogenous inertial components, a dedicated paradigm based on a wavelet multi-resolution strategy has been implemented [Andò et al., 2014b]. The proposed solution is in line with the concept of output-only analysis of structural response which estimates the modal parameters by analyzing the response to environmental actions (such as wind or traffic) instead of using expensive equipment to provide inertial input to buildings [Federici et al., 2012].

In the next section a brief overview of the system proposed is given, with specific regards to the multi-sensor node and the user interface developed. Laboratory tests aimed to validate the behavior of the developed multi-sensor node are also presented.

Section II also presents cases of study with the multi-sensor node installed in real sites. The use of the Wavelet based signal processing is shown in Section 3.

2. THE MULTI-SENSOR NODE: DEVELOPMENT AND CHARACTERIZATION

2.1 THE DISTRIBUTED SENSOR NETWORK

Each node is aimed to detect accelerations and tilts with a resolution of 0.02 g (0.2 m/s^2) and 0.004°, respectively. The inspected frequency range is (0.5 - 10.0) Hz, while a sampling rate of 200 Hz has been used.

In particular, the following MEMS sensors have been used: the tri-axis accelerometer MMA7361L, by Freescale Semiconductor, to measure accelerations along the x, y and z axis, and two SCA61T-FAHH1G inclinometers by Murata to measure both pitch and roll angles. A 16 bit Analog-to-Digital Converter (ADC) has been included to acquire signals coming from the two inclinometers. The solution available for the network connection exploit the ZigBee/IEEE 802.15.4 compliance protocol. To this purpose, the XBee-PRO modules @ 2.4 GHz by Digi International Inc. have been used and connected through the Wireless SD Shield to the Arduino board. The gateway node has been implemented through

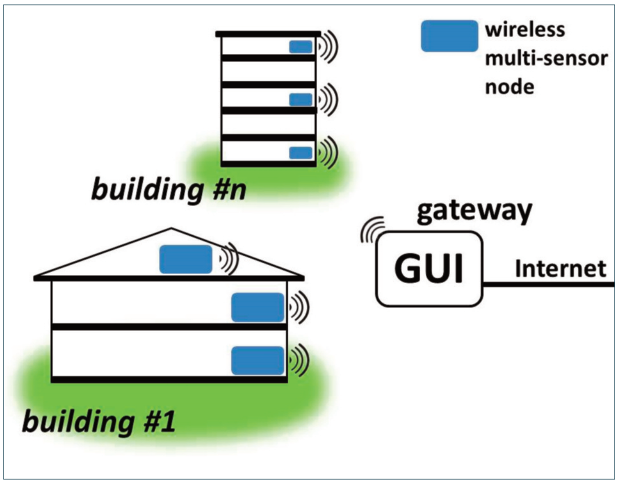


FIGURE 1. Schematization of the position of the multi-sensor nodes inside the buildings: on the basement, on the top and in a middle height. Devices can communicate with a remote server by a wireless connection.

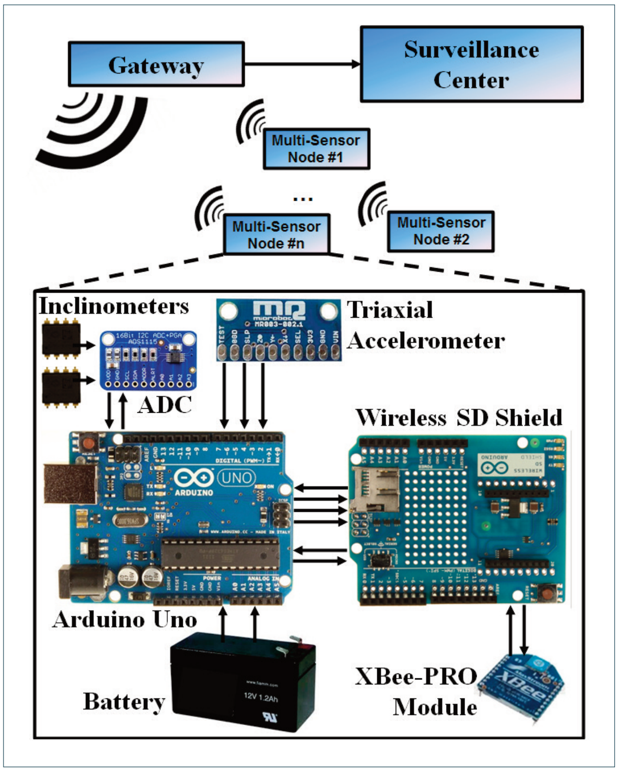


FIGURE 2. Schematization of the developed multi-sensor node.

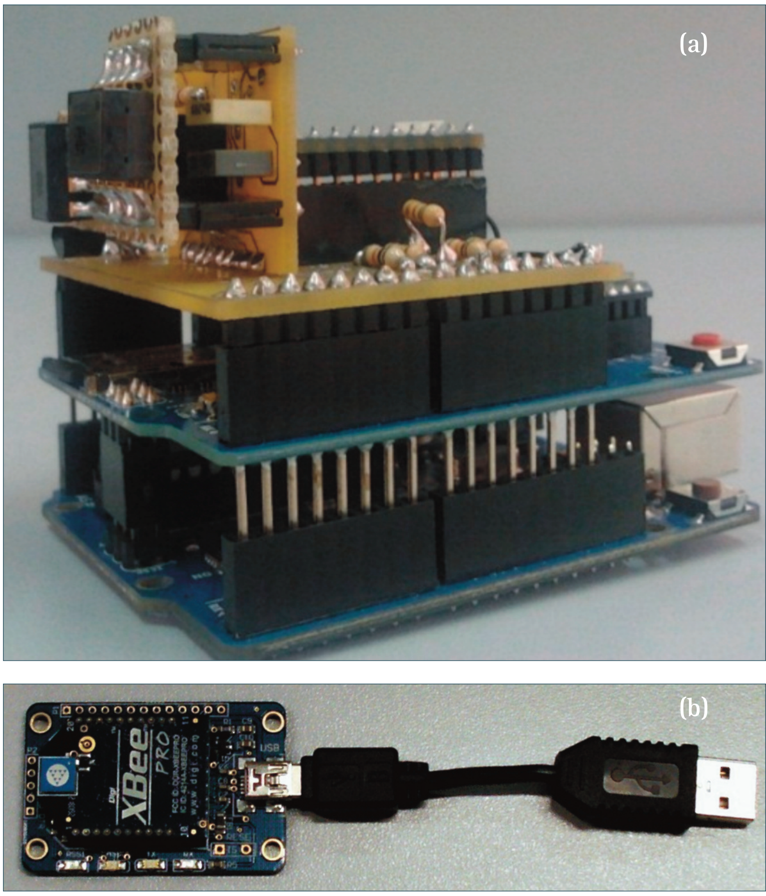


FIGURE 3. Real views of the developed system: (a) the multi-sensor node; (b) the gateway node.

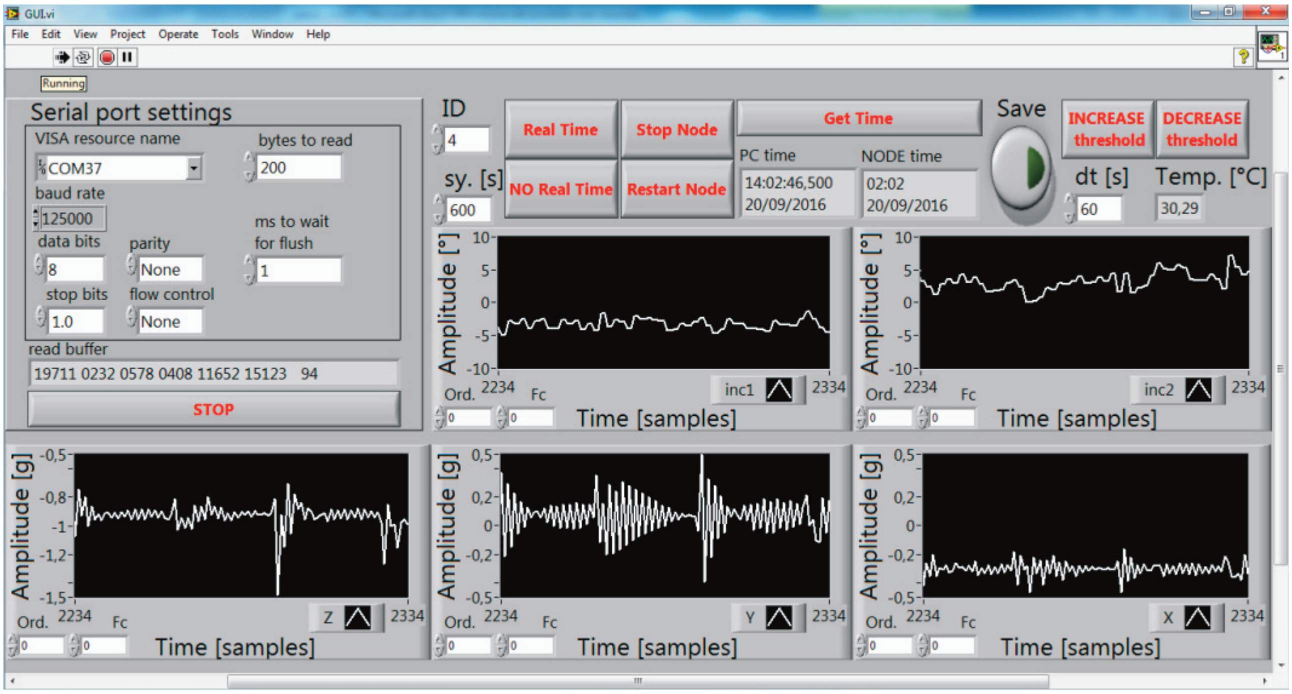
the XBee-USB board, which allows for connecting a XBee-PRO module to the PC through a USB interface.

A rechargeable battery has been used to power the whole device in case the main power is missing. For this purpose, the battery capacity has been chosen to feed the multi-sensor node for about 24 hours. The stacked structures of the multi-sensor node and the gateway are shown in Figure 3 [Andò et al., 2014a].

Two operating modes for data transfer have been implemented: continuous data transfer and event triggered. In the first case, data provided from sensors are continuously transferred to the remote server, where further signal elaboration is accomplished to extract deep information from acquired data [Andò et al., 2014b]. The event triggered mode is implemented through a dedicated algorithm running on the microcontroller. The paradigm performs a data pre-filtering to start a data transmission of 5 seconds to the remote server in case a supra-threshold event occurs. In particular, a supra-threshold event is characterized by an acceleration value which exceeds a prefixed threshold value. Such threshold value is fixed by computing the noise floor in the acceleration signal in the absence of external stimuli.

Data acquired from the multi-sensor nodes are locally stored by a micro SD card writer and eventually conveyed by a wireless connection to a remote server (Surveillance Center), where the Graphical User Interface (GUI) shown in Figure 4 is running.

In the current configuration, which has been realized for the sake of proof-of-concept of the developed sensing methodology, data are stored on the multi-sensor node, while the gateway and the monitoring station (in



VISA resource name: COM37
bytes to read: 200
baud rate: 125000
data bits: 8
parity: None
ms to wait for flush: 1
stop bits: 1.0
flow control: None
read buffer: 19711 0232 0578 0408 11652 15123 94
ID: 4
sy. [s]: 600
PC time: 14:02:46,500 20/09/2016
NODE time: 02:02 20/09/2016
dt [s]: 60
Temp. [°C]: 30,29

FIGURE 4. Graphical User Interface (GUI) adopted for the sake of data representation and signal processing.

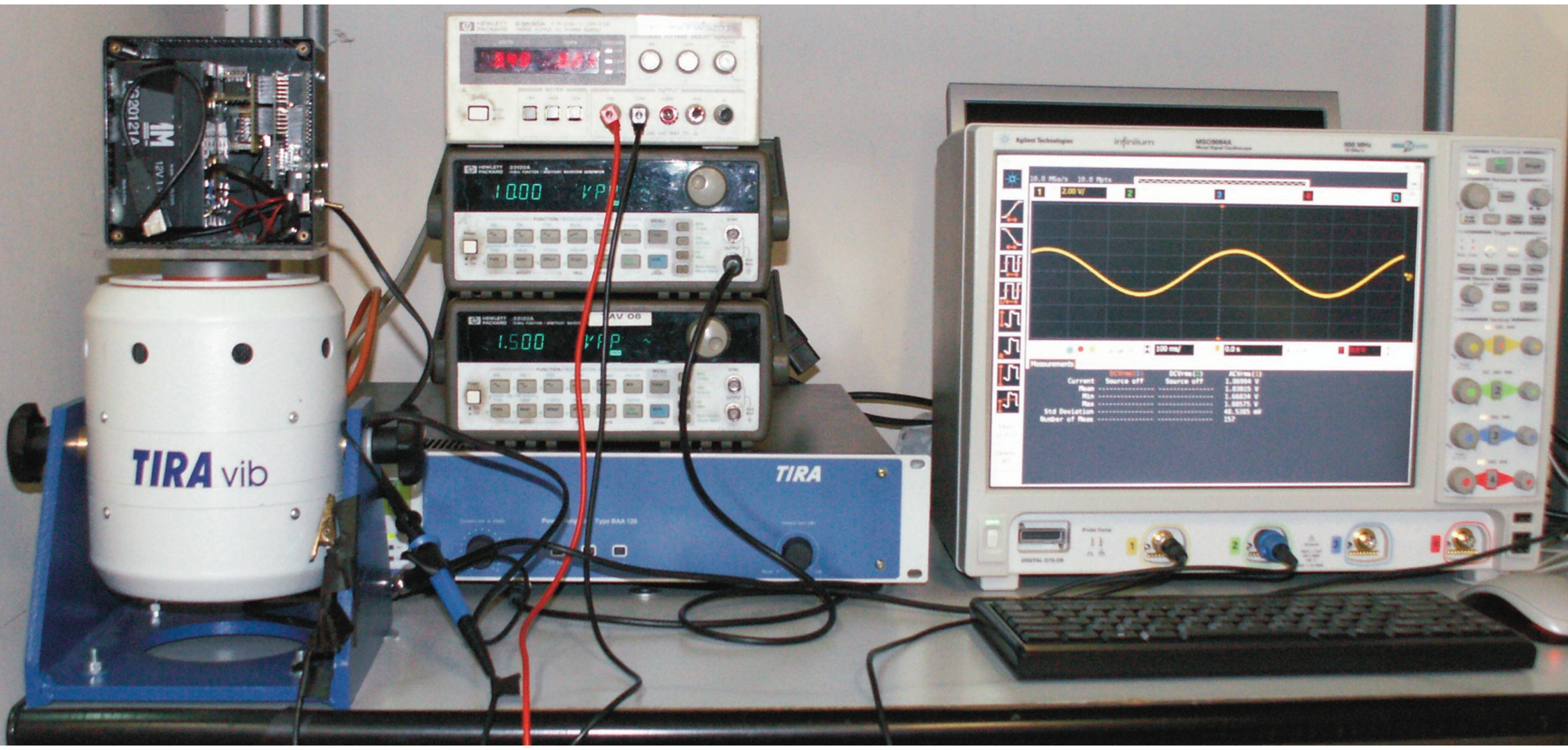


FIGURE 5. Experimental set-up adopted for the characterization of the multi-sensor node.

the future the Surveillance Center) have been implemented by the XBee-USB board cabled via a USB interface to a PC. The GUI is in charge to set the communication parameters with the gateway, to show the rough data acquired and to set the operating mode of the generic multi-sensor node. If a continuous data transfer is enabled, the time evolution of data gathered by sensors is shown. In case of the event triggered operating mode, the GUI will receive data only in the presence of a detected event. Moreover, the GUI is used to convey a clock signal to the whole set of multi-sensor nodes, for synchronizing their internal clock to the re-

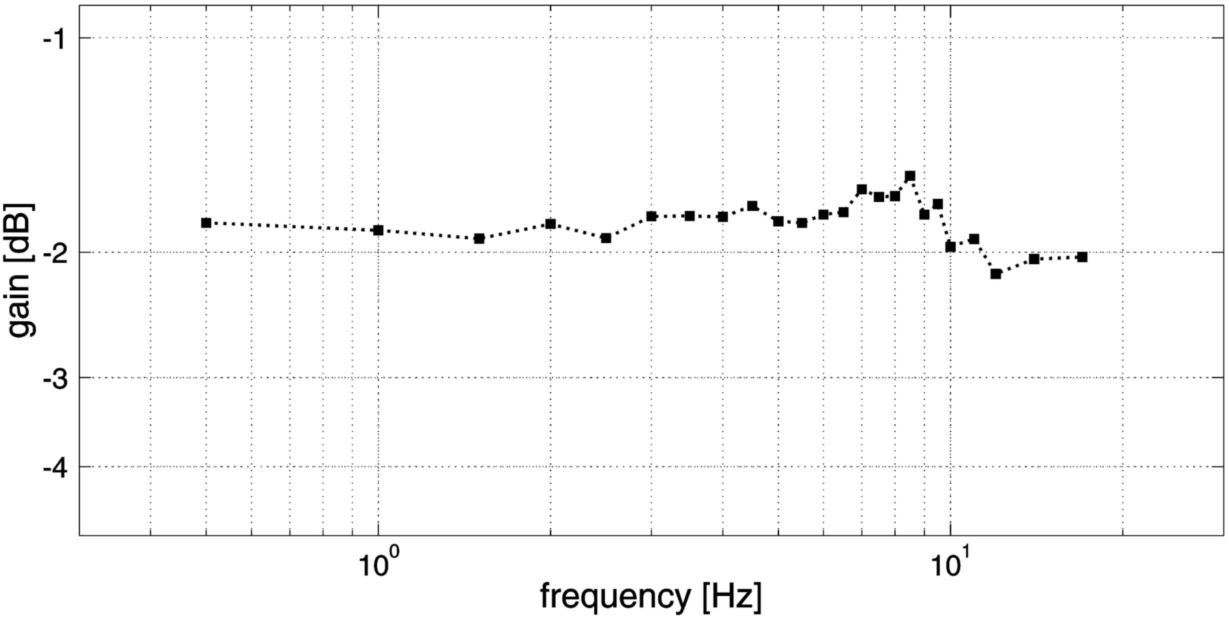


FIGURE 6. Frequency response of the acceleration module embedded in the multi-sensor node.

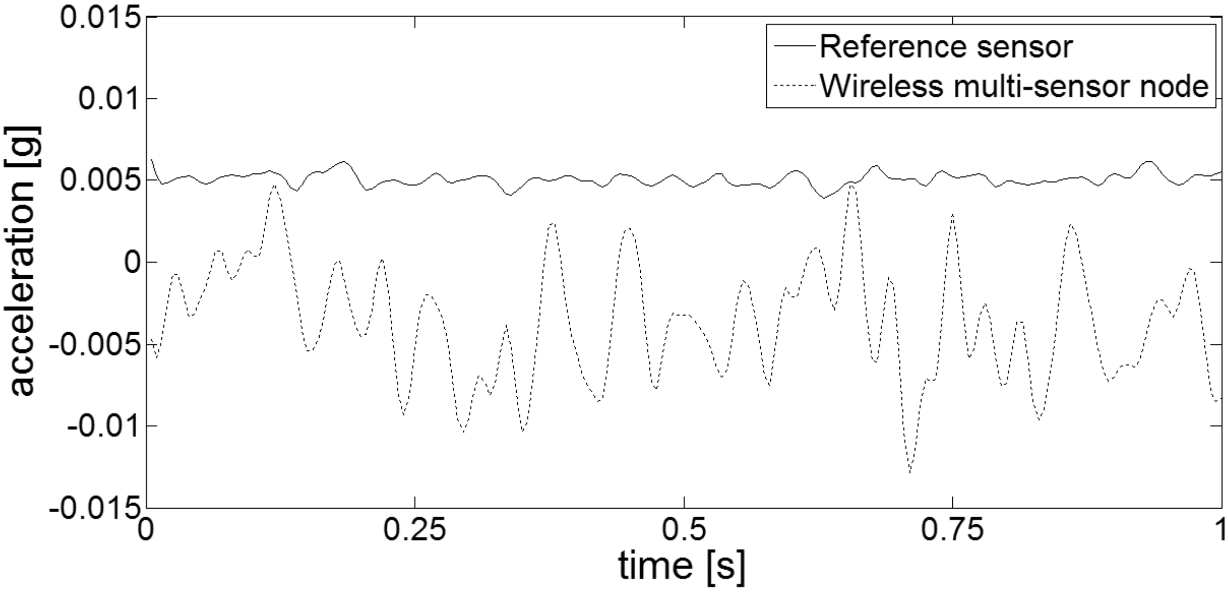


FIGURE 7. Comparison between acceleration signals from the reference sensor (solid) and the wireless multi-sensor node (dotted) without solicitations.

mote server, in turn synchronized with an absolute time reference; the synchronization frequency is chosen by the user (e.g. once every ten minutes or hourly). Adjustable (in terms of order and cutoff frequency) low-pass Butterworth filters have been also implemented.

2.2 CHARACTERIZATION OF THE MULTI-SENSOR NODE

To evaluate performances of the overall system developed, laboratory tests on the wireless multi-sensor node were carried out by a vibrational system.

The experimental set-up adopted for the sake of system characterization is shown in Figure 5. Main components of the set-up are: the shaker (consisting of a movable platform actuated by a vibration exciter), a power amplifier, a function generator and a reference accelerometer (model 333B40 by PCB Piezotronics Inc.) aimed to perform an independent measurement of stimulations applied to the multi-sensor node.

Signals acquired by the multi-sensor node have been stored in the internal microSD card. In addition, through the wireless link, these signals have been dis-

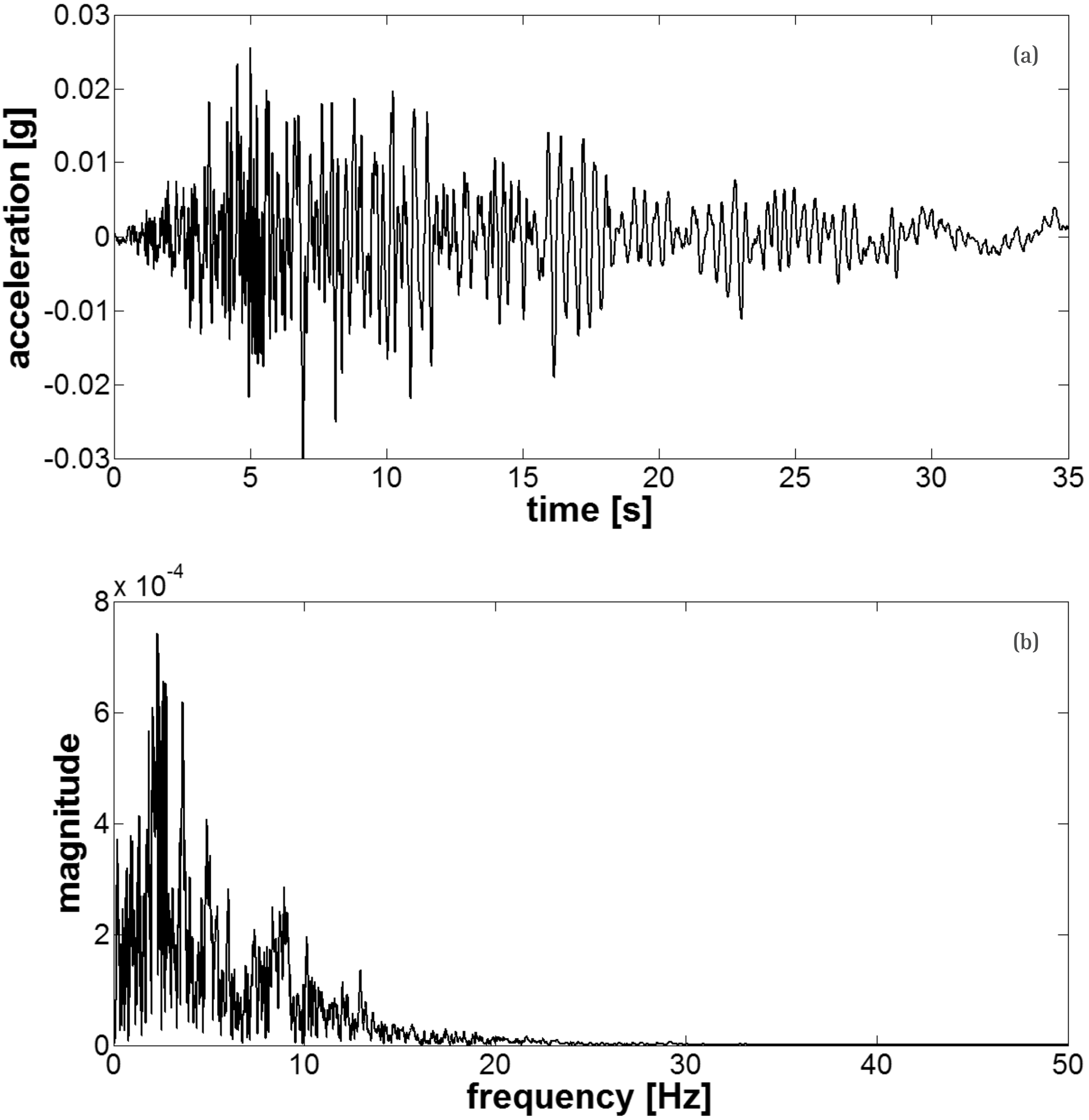


FIGURE 8. Seismic sequence recorded during a real earthquake: (a) time-domain signal and (b) frequency content.

played on the GUI installed in a laptop computer. Signals provided by the reference accelerometer have been acquired through a DSO-X 3024A oscilloscope by Agilent Technologies. This configuration allows to acquire data from the multi-sensor node and the reference accelerometer at 200 Hz and 1 MS/s, respectively.

The vibration exciter is the S 51110 from TIRA GmbH, an electrodynamic transducer with wide frequency range which can generate a sinuous force of 100 N. The exciter operates within a frequency band of (2 - 7000) Hz and can be controlled with either a sinus wave signal or a random signal. The exciter is pivoted and can be fixed to operate in vertical or horizontal direction by a turnbuckle. The transfer of vibrations to the site is damped by the swivel-frame. The vibration exciter was driven by the power amplifier BAA 120 from TIRA GmbH. It is an air-cooled, universally applicable amplifier with a nominal output of 120 VA.

To generate the test signals, the Agilent 33120A function generator was adopted. It is a versatile benchtop device with built-in arbitrary waveform capability.

Experimental tests were performed stimulating the wireless multi-sensor node with sinusoidal dynamics applied along the vertical direction. For this purpose, the wireless multi-sensor node was clamped on the plexiglass platform, in turn screwed on the movable

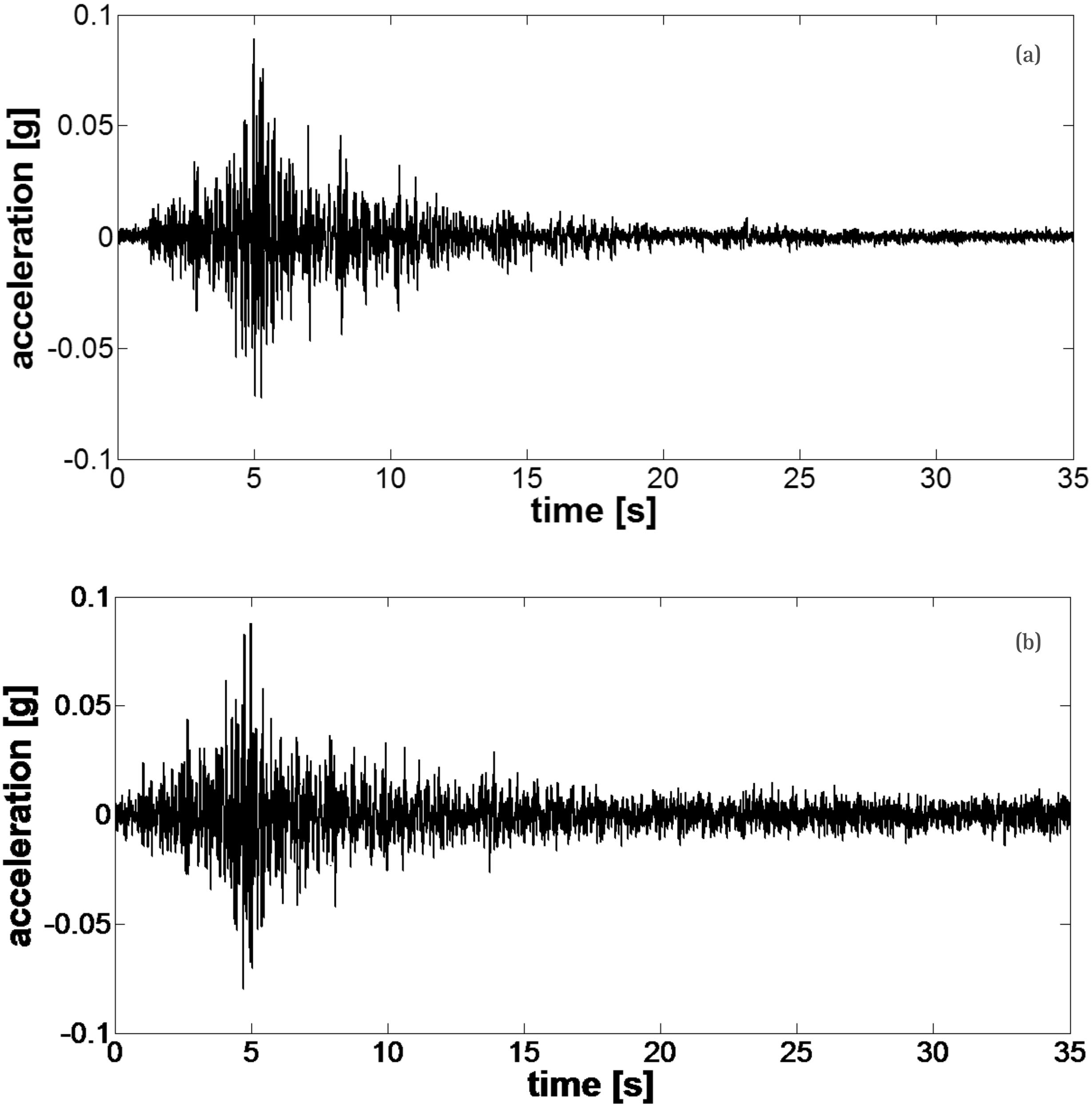


FIGURE 9. Acceleration signals recorded (a) by the reference accelerometer and (b) the multi-sensor node when a simulated earthquake is forced by the shaker system.

bolt of the vibration exciter. Sinusoidal stimuli with amplitude between 0.01 g (0.1 m/s^2) and 1 g (9.81 m/s^2), in the frequency range (0.5 - 17) Hz have been used. Although the lower limit of the frequency range to be analyzed is out of the frequency band declared for the TIRA shaker, the latter can still operate below 2 Hz, especially considering the low acceleration values imposed during the characterization phase. Moreover, it should be observed that the acceleration has been independently measured by the reference accelerometer, whose operating range is compatible with the target range to be analyzed. Signals coming from the reference sensor and the multi-sensor node were processed by a mean value removal procedure and a second order low-pass filter with cutoff frequency f_C = 30 Hz.

The estimated frequency response of the acceleration module embedded in the multi-sensor node is shown in Figure 6. Performances of the acceleration module in terms of resolution and noise floor have been estimated by observing the system behavior in the absence of external stimuli. Figure 7 shows the comparisons between acceleration signals recorded by the reference device and the wireless multi-sensor node, without solicitations. The resolution, estimated by the signal standard deviation in the 1 σ level, is 0.007 g (0.07 m/s^2); the noise floor, obtained by estimating the power spectral density value @1Hz, is 0.008 g/√Hz (0.08 m/s^2/√Hz).

2.3 LABORATORY EXPERIMENTS AIMED TO COMPARE THE SYSTEM DEVELOPED WITH COMMERCIAL DEVICES

In order to assess performances of the multi-sensor node in case of seismic stimuli, several experiments have been performed.

The first experiment was aimed to test the system performances to a real seismic stimulation. Data from a real seismic event has been used to stimulate the multi-sensor node by the experimental set-up above described. The vertical component (along the *z* axis) of a seismic sequence recorded during the earthquake occurred in the region Emilia (Pianura Padana area, Italy), downloaded from the website of the Istituto Nazionale di Geofisica e Vulcanologia (INGV), is shown in Figure 8a.

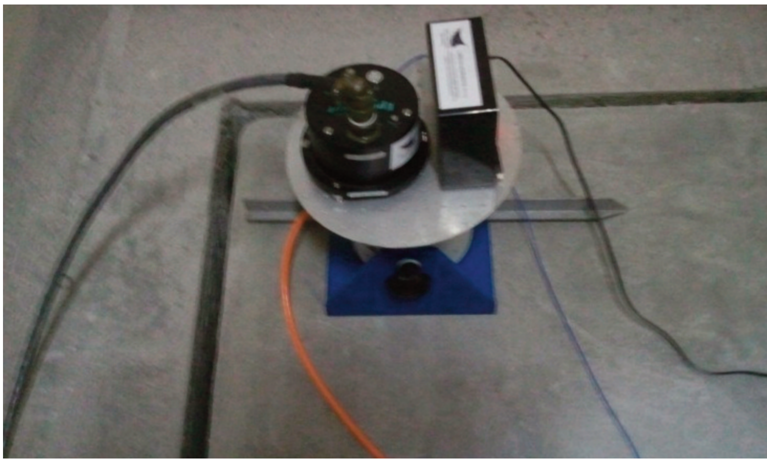


FIGURE 10. Acceleration signals recorded (a) by the reference The multi-sensor node and a commercial accelerometer EpiSensor ES-T by Kinematrics Inc. placed on the moving platform of the shaker.

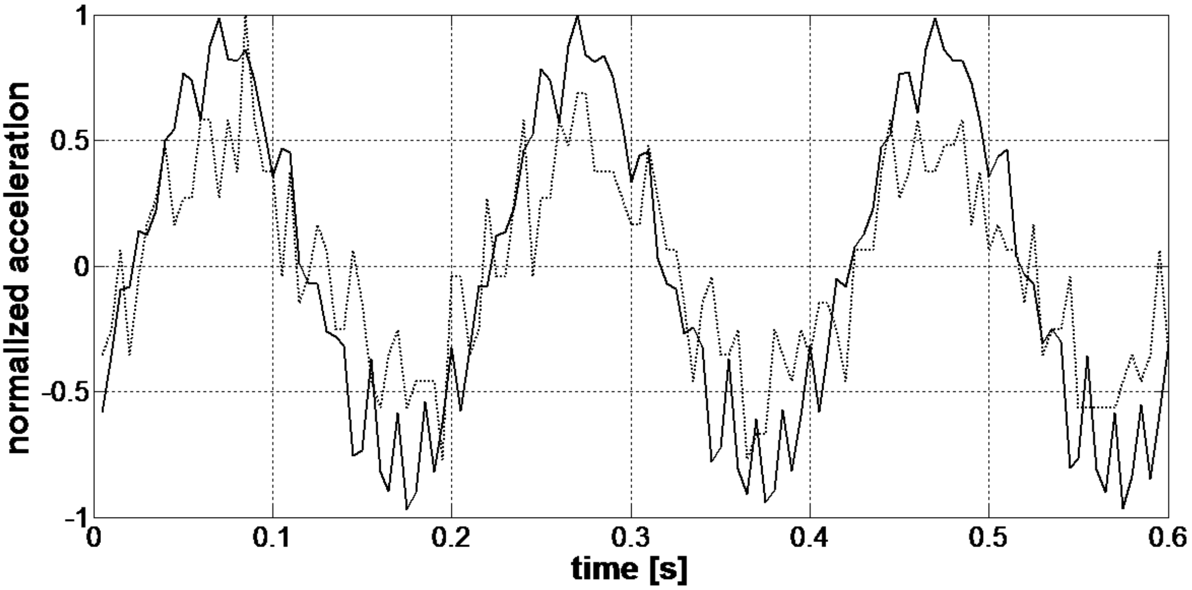


FIGURE 11. Comparison between the normalized responses of the EpiSensor ES-T accelerometer (solid) and the multi-sensor node (dotted) to a sinusoidal acceleration.

It was acquired during the earthquake of May 20 in 2012 (event depth: 6.30 km; magnitude: 5.9; epicentral distance: 36.45 km), between 02:03:52 and 02:04:27 GMT. This signal has been detected by an accelerometer EpiSensor ES-T by Kinematrics Inc., resampled at a frequency of 100 Hz, and filtered with a 4th order Butterworth band-pass causal filter [Boore and Akkar, 2003], in order to remove the high and low-frequency noise.

The filter cut-off thresholds are 0.1 Hz and 40 Hz respectively. The frequency content of the signal, shown in Figure 8b, highlights the dominant components located around 2 Hz and a meaningful content up to 15 Hz.

The signal shown in Figure 8a has been uploaded into the function generator and then forced into the shaker system. The corresponding acceleration signals recorded by the reference accelerometer and the multi-sensor node, after a filtering operation, are shown in Figure 9a and 9b, respectively.

This experiment demonstrates the potentiality of

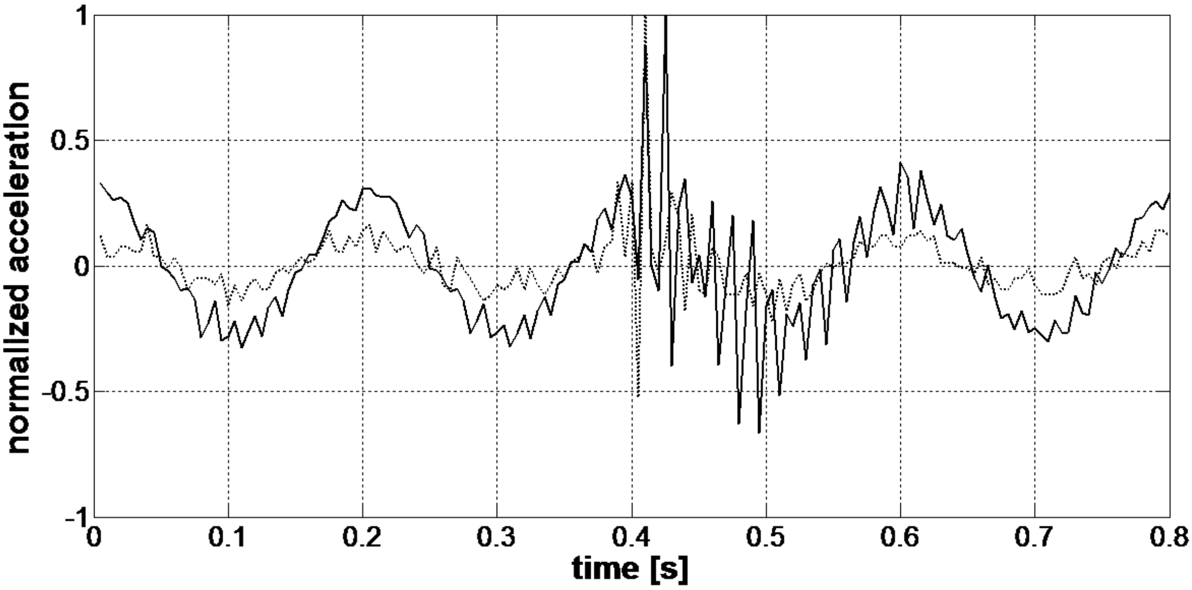


FIGURE 12. Comparison of the normalized responses of the EpiSensor ES-T accelerometer (solid) and the multi-sensor node (dotted)to a sinusoidal stimulus with superimposed impulsive solicitations.

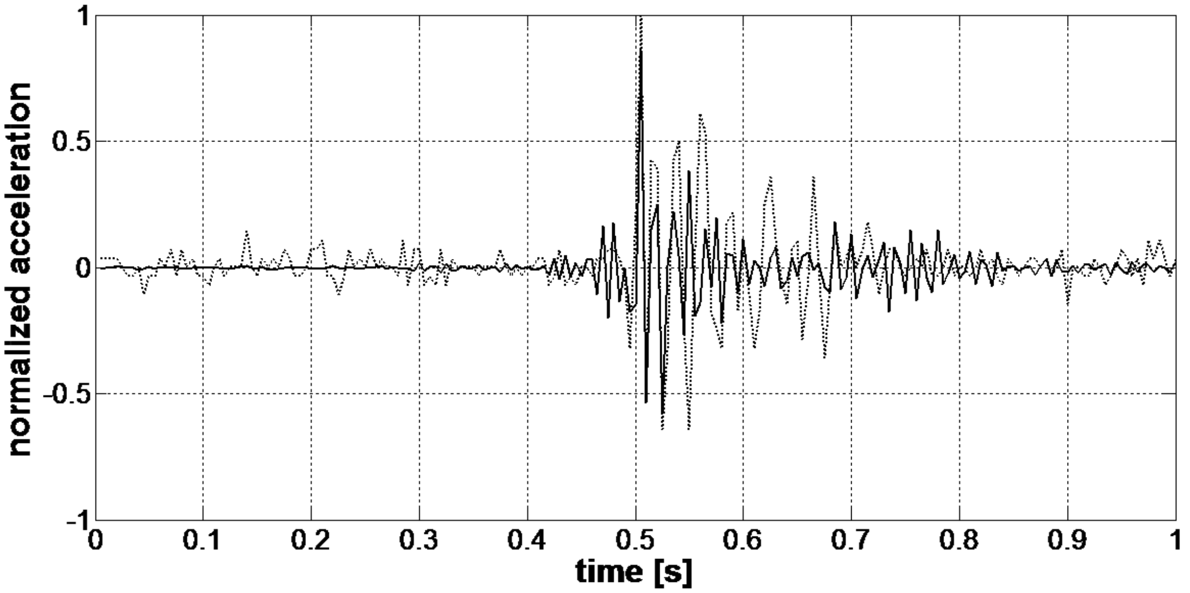


FIGURE 13. Signals acquired by the EpiSensor ES-T (solid) and the multi-sensor node (dotted) on November 27, 2014 at 3:30:35 GMT.

the multi-sensor node to detect events from seismic sources. The second experiment has been dedicated to compare the responses of the multi-sensor node and a commercial accelerometer to solicitations along the vertical axis. As shown in Figure 10, in order to provide the same acceleration, the multi-sensor node and the reference EpiSensor ES-T by Kinemetrics Inc. have been positioned on the moving platform of the shaker. The shaker was placed on a concrete plinth isolated by exogenous stimuli.

Figure 11 compares the normalized responses of the multi-sensor node and the EpiSensor ES-T accelerometer to a sinusoidal acceleration with amplitude and frequency of about 0.02 g (0.2 m/s^2) and 5 Hz. The latter values have been chosen within the project specifications (resolution 0.02 g (0.2 m/s^2), frequency range 0.5 Hz to 10 Hz). Normalized responses have been calculated by dividing the acceleration signals for the re-

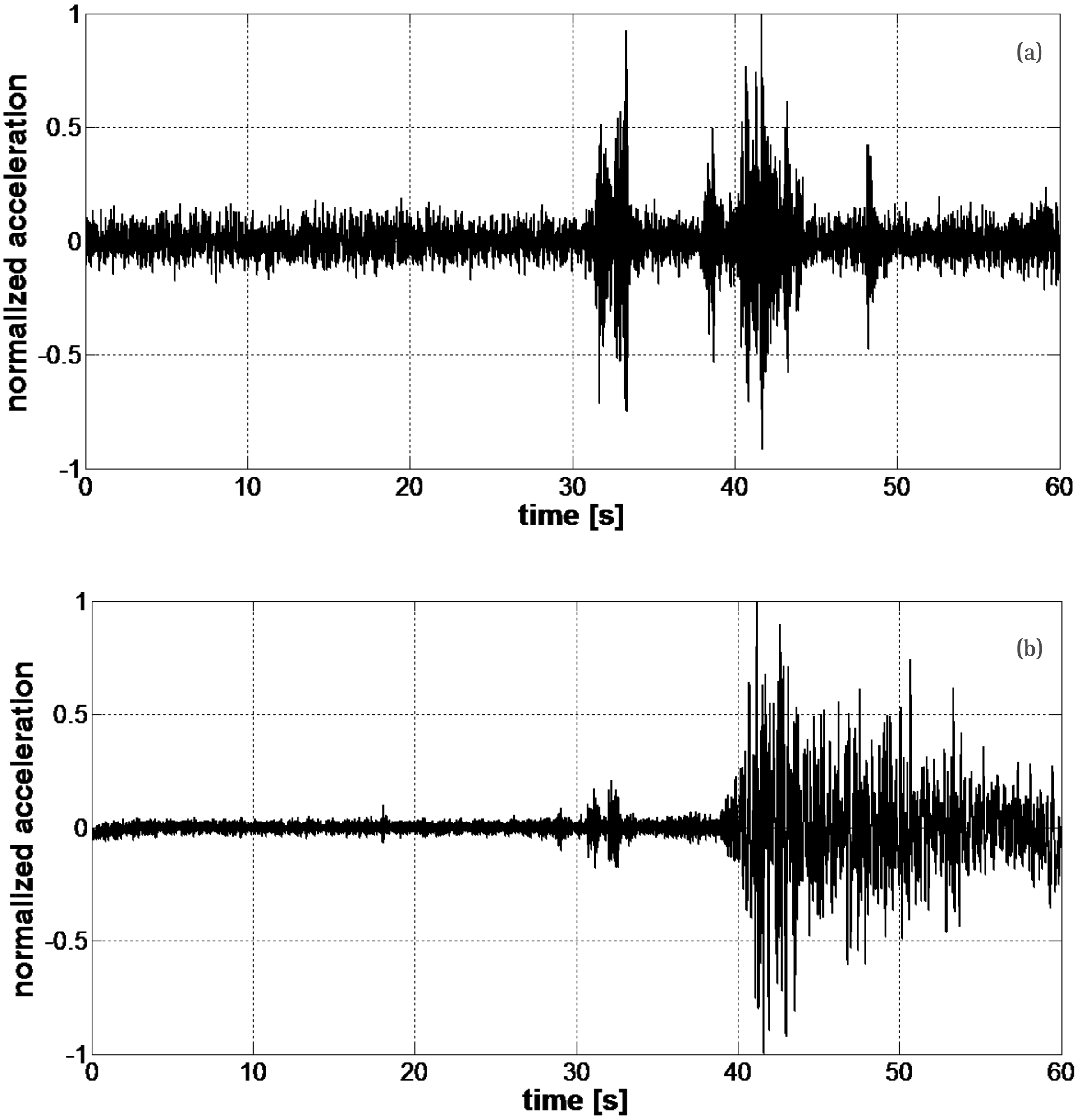


FIGURE 14. Earthquake of 9 May 2015, at 08:22:41 GMT, in the Tyrrhenian Sea, filtered and normalized: (a) acquired by the multi-sensor node and (b) recorded by the closest monitoring station of the INGV (MZZ).

spective peak values contained in the time sequences considered.

Finally, with the multi-sensor node and the EpiSensor ES-T placed on the movable platform of the shaker (still excited with the sinusoidal force), the concrete plinth has been repeatedly solicited to compare the impulse response of the devices. Figure 12 shows the comparison between the normalized signals acquired by the two devices. Above results, either in case of a real earthquake or a sinusoidal acceleration, demonstrate the congruity between responses provided by the multi-sensor node and commercial devices. Of course it must be taken into account that the multi-sensor node developed aims to provide rough information on the structural response of the monitored structure, with a lower level of accuracy with respect to professional instrumentation. The quality informations provided can be increased by data redundancy, achieved through the installation of several multi-sensor nodes in the same structure.

2.4 EXPERIMENTAL SURVEYS IN REAL SITES

In the following, the most relevant results of experimental surveys carried out in real application contexts are reported. The multi-sensor node has been installed in continuous acquisition with the aim to detect seismic and anthropic signals: i) at the INGV in Catania-Italy, and ii) in a public building in Messina-Italy.

In the first site the multi-sensor node has been installed on the third floor of the building in the South-East corner. The commercial accelerometer EpiSensor ES-T by Kinematrics Inc. has been also installed as a reference system. Figure 13 shows a 1 s time frame of signals recorded by the two instruments on November 27, 2014 (around 3:30:35 GMT). A suitable matching between the two normalized records emerges, especially corresponding to the part of the two signals conveying a meaningful piece of information. With regard to the installation of the multi-sensor node in the public building in Messina, an event has been detected on 9 May 2015 at 08:22:41 GMT during an earthquake occurred in the Tyrrhenian Sea. This event has been also reported by an official seismic bulletin of the INGV. The time-domain acceleration signals, acquired by multi-sensor node and by the closest monitoring station of the INGV (named MZZ), are shown in Figs. 14. These signals (both acquired at 200 Hz) have been filtered with a fourth-order Butterworth band-pass filter to attenuate the low and high frequency noise. The cut-off frequencies have been set at 0.1 Hz and 40 Hz [Boore and Akkar, 2003], respectively. Moreover, the signals have been normalized. Also in this case, the two signals (Figure 14a and Figure 14b) appear synchronized.

3. A WAVELET APPROACH TO FILTER ACQUIRED SIGNALS

The proposed wavelet approach to analyze acquired signals and filter out exogenous information is schematized in Figure 15. As first, the vertical component of the acceleration signal provided by the multi-sensor node has to be decomposed in one approximation level and several details levels using the Discrete Wavelet Transform (DWT) operator. Each detail level is compared with patterns resembling human activities, in terms of amplitude and frequency content [Roundy et al., 2003]. Detail levels showing high correlation with such patterns have to be removed. The remaining components of the vertical acceleration signal are then reassembled. The obtained signal is expected to contain potential responses of the structure monitored to external signals belonging to the seismic domain. With the aim to assess performances of the proposed approach, the multi-sensor node has been stimulated in the vertical direction by a dedicated test signal provided through the shaker. In order to mimic frequencies of typical environment patterns [Roundy et al., 2003] and candidate seismic sources, the adopted signal is the concatenation of sinusoidal accelerations at different amplitudes and frequencies. The test signal, in the time and frequency domains, is shown in Figure 16a and 16b, respectively. Figure 17 shows the time-frequency analysis of the vertical acceleration component recorded by the wireless multi-sensor node, obtained by computing the wavelet coefficients. Following the approach sketched in Figure 15, such signal has been then decomposed in one approximation level and several detail levels using the DWT. The obtained results are shown in Figure 18. The next step requires the comparison between each detail level and the human generated patterns [Roundy et al., 2003]. Detail levels showing an high correlation with typical human patterns have been removed and the residual detail levels have been reassembled to produce the filtered signal. The DWT of the filtered signal is shown in Figure 19. By comparing the wavelet coefficients of the re-

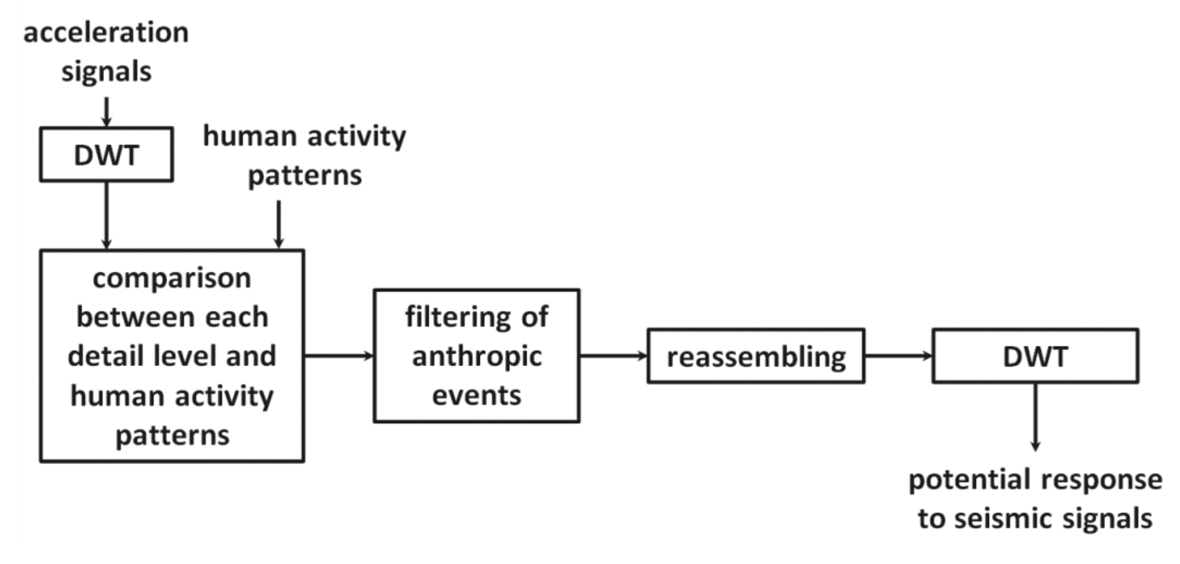


FIGURE 15. Schematization of the proposed wavelet approach to analyze the acquired signals.

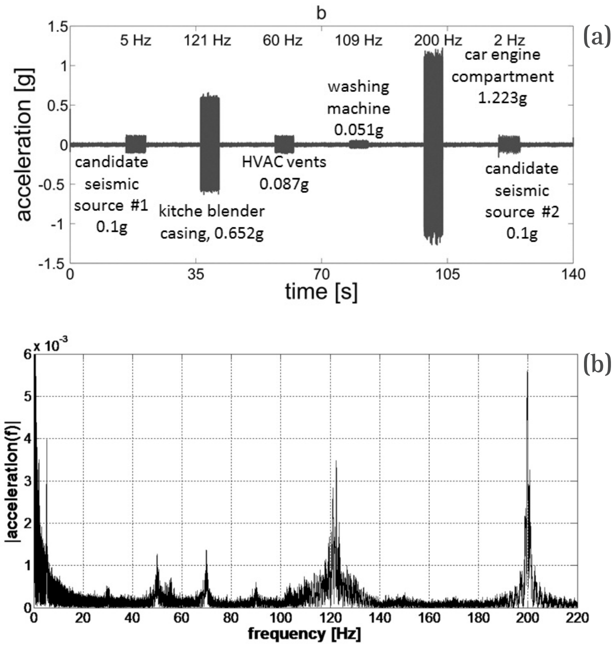


FIGURE 16. Test signal to stimulate the multi-sensor node in the vertical direction: (a) time-domain evolution, (b) frequency content.

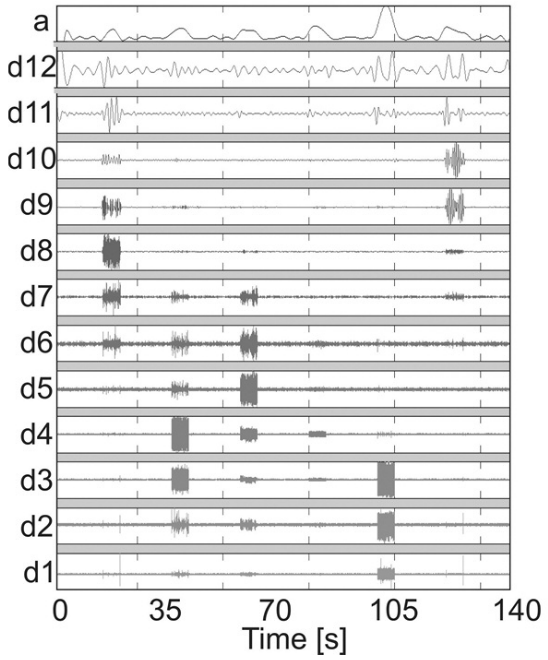


FIGURE 18. Discrete wavelet decomposition of the vertical acceleration signal.

assembled signal, shown in Figure 19, with results in Figure 17, it is possible to observe that exogenous components in the input signal have been significantly reduced, while seismic related components of the signal are clearly evincible. The experimental test demonstrates performances of the proposed wavelet approach to separate seismic sources from other exogenous patterns. Effectively, nowadays, many times has been discussed on the advantages of the wavelet approach if compared with other techniques like the Fourier transform [Sifuzzaman et al., 2009], especially for non-stationary and complex behavior of time series like that of geophysical signals [Chamoli, 2009]. Moreover, the wavelet analysis provides a good separation of the long-period component from the short-period and allows for investigating the local features of the signal with a level of detail matched to their characteristic scales [Greco et al., 2010].

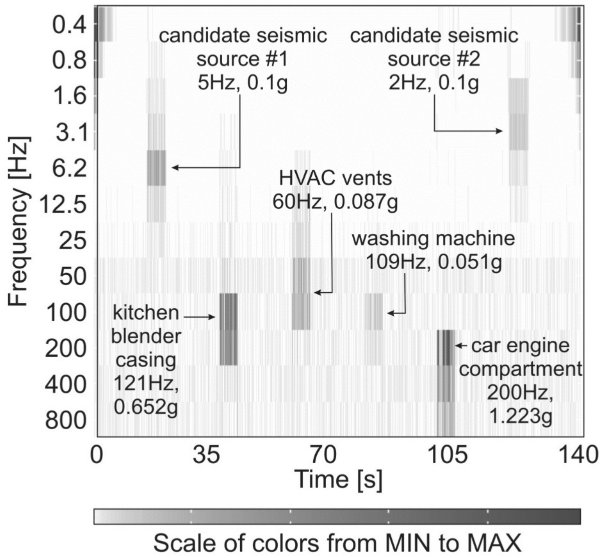


FIGURE 17. Time-frequency image of the vertical acceleration measured by the multi-sensor node, in case of the mechanical input shown in Figure 16a.

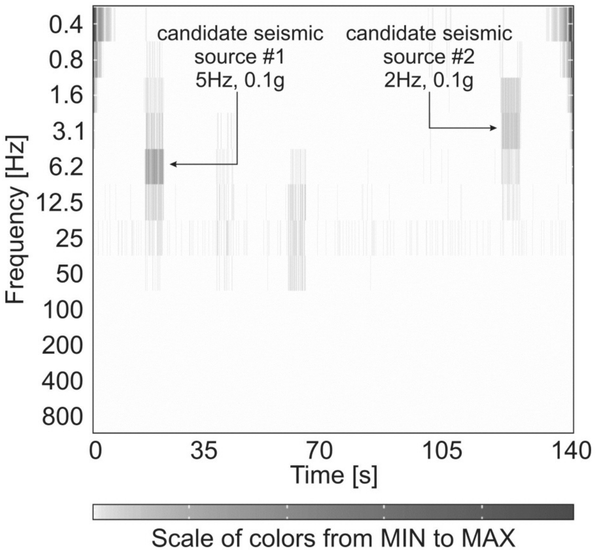


FIGURE 19. DWT computed on the filtered vertical acceleration signal.

4. CONCLUSIONS

Results obtained encourage the use of the proposed methodology for the development of low cost systems to investigate the seismic response of buildings. Several experiments have been performed to demonstrate the good response of the multi-sensor node if compared to the response of commercial devices. A methodology to isolate candidate responses of the structure to seismic stimuli has been developed.

Main outcome of the strategy presented through this paper resides in the possibility to develop low cost early warning systems with high spatial resolution and continuous operation.

Future efforts will be dedicated to implement more sophisticated signal processing aimed to improve the device performances in terms of detection of supra-threshold events.

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