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A Low Cost Multi-Sensor Strategy for Early Warning in Structural Monitoring Exploiting a Wavelet Multiresolution Paradigm

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Abstract

This paper deals with a novel approach to validate alerts provided by an early warning system (EWS) for structural monitoring implemented through low cost multi-sensor nodes. In particular, a dedicated wavelet multiresolution methodology is presented to implement a reliable assessment of the structural behavior. Such strategy allows to discriminate the structural response to seismic sources from other exogenous inertial components. Results obtained demonstrate the suitability of the proposed solution in the framework of the development of low cost multi-sensor strategies for the early warning of anomalous structural behaviors.

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*Keywords:*structural monitoring; early warning system; low cost-embedded system; multi-sensor node; wavelet based paradigm.

1. Introduction

Efficient structural monitoring is mandatory especially in seismic areas. Standard solutions for structural monitoring are very accurate, while providing spare information over the time with a poor spatial resolution [1]. The availability of an early warning system (EWS) for the early detection of structural failures would be of primary interest especially for high risk environments like schools or public buildings. An early warning system can be defined as a multifunctional system including sensors, signal processing and communication facilities aimed to timely provide information useful to prepare resources and response actions to minimize the impact of the incoming hazard [2].

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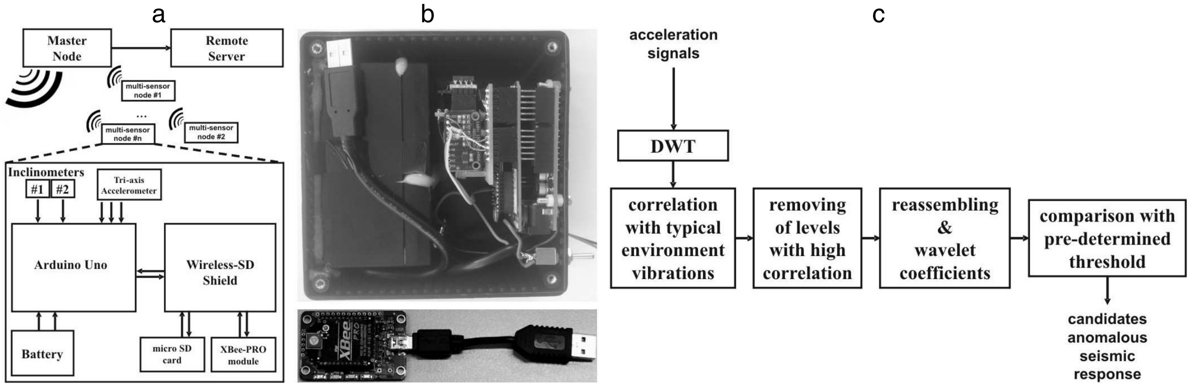

Fig. 1. (a) schematization of the developed multi-sensor strategy for early warning in structural monitoring; (b) real view of the wireless multi-sensor node and the master node; (c) the methodological approach to investigate performances of the proposed strategy.

Seismic early warning systems for the process industry, in terms of relations between structural monitoring, seismic reliability of equipments and industrial quantitative risk, are analyzed in [3].

Due to the devastating effect of geohazards in settlement areas and the need for precise monitoring systems to protect human life and property, in [4] a prototypic EWS for different types of landslides using wireless sensor networks (WSN) for real-time monitoring has been developed. This system allows to monitor direct deformations caused for example by landslide movements, but also indirect deformations on buildings and constructions, like bridge or retaining walls.

Other examples of EWSs for structural monitoring are described in [5,6,7]. A review of the literature on EWSs, the level of utilization of remote sensing technology and the potential trends for future systems is outlined in [8].

Low cost multi-sensor approaches for early warning in structural monitoring are strategic to assure time continuous and spatially distributed observations [9].

In this paper a low cost approach for early waning in structural monitoring is proposed. The system presented uses a low cost multi-sensor platform and a wavelet multiresolution strategy to discriminate the structural response to seismic sources from other exogenous inertial components. The methodology proposed, perform a decomposition of signals provided by the multisensor node into a low-resolution approximation level and several detail levels through the Discrete Wavelet Transform (DWT). By removing detail levels strongly correlated with typical environment vibrations, the residual time-frequency image would evidence candidate structural responses to seismic sources. The processing paradigm runs in a remote server collecting data from a WSN implementing the monitoring system. Main advantages of the proposed strategy are related to performances of the signal processing proposed, the low cost and low power characteristics of the hardware, and the reduced dimensions of the multi-sensor nodes.

2. The multi-sensor node and the methodologic approach for the early warning in structural monitoring

A schematization of the developed multi-sensor strategy for early warning in structural monitoring is shown in Fig. 1a. The WSN, which provides a reliable routing of sensors data to the remote server, consists of wireless multi-sensor nodes, a master node and a dedicated Graphical User Interface (GUI).

Each wireless multi-sensor node is aimed to detect seismic stimuli (accelerations) and tilts with a resolution of 0.02 g and 0.004 °, respectively. The inspected frequency range is (0.5 - 10) Hz while a sampling rate of 200 Hz has been used. Real views of the wireless multi-sensor node and the master node are shown in Fig. 1b [9].

The multi-sensor node architecture exploits the Arduino Uno microcontroller board. The microcontroller board is connected with sensors and other resources embedded in the multi-sensor node, acquires data from the sensors and manage the communication protocols of the WSN.

The Wireless SD Shield by Arduino has been used to communicate to the remote server through the XBee-PRO module by MaxStream. The XBee-PRO module has an operating range up to 100 m in indoor environment or 1500 m in outdoors (with line-of-sight).

In order to implement the autonomous operation mode for data collection, the micro SD card embedded in the Wireless SD Shield is used.

A MEMS-based tri-axis accelerometer MMA7361L by Freescale Semiconductor has been chosen to measure accelerations along the x, y and z axis. It has a low power consumption (2.2 V - 3.6 V, 400 μA), selectable operating range (1.5 g or 6 g) and high sensitivity (800 mV/g @ 1.5 g). The power spectral density is 350 μg/ √ Hz.

To measure both the radial and tangential inclinations, two SCA61T-FAHH1G inclinometers by Murata have been used. The devices are MEMS-based single axis inclinometers with high resolution (up to 0.0025 °) and low current consumption (2.5 mA, 5 V).

A customized board embedding above mentioned sensors has been developed and connected on the top of the Wireless SD Shield which is in turn connected to the Arduino board. The stacked structure of the multisensory node is shown in Fig. 1b. A rechargeable lead-acid battery has been used to power the wireless multi-sensor node.

The master node has been implemented through an XBee-USB adaptor which allows for connecting an XBee-PRO module to the PC. The device is then directly connected to a USB port furnishing the required power supply.

Two operating modes have been implemented: real-time data transfer and event triggered. In the first case, data provided from sensors are continuously transferred to the remote server where a further signal elaboration is accomplished to extract deep information from data. In the second case, suitable algorithms running on the microcontroller device will perform data pre-filtering to start with a continuously data transfer to the remote server when supra-threshold events occurs.

A LabVIEW GUI interface has been developed. Main tasks performed by the interface are delivering alarms in case of critical events occurs, showing the time evolution of data gathered by sensors (when the real time data transfer is enabled) and to retrieve data stored in the micro SD card on user demand.

The proposed strategy for early warning in structural monitoring is schematized in Fig. 1c. As first, the vertical component of the acceleration signal provided by the multisensory node has to be decomposed in an approximation level and several details levels using the Discrete Wavelet Transform (DWT). Each detail level is compared with amplitude/frequency modes typical of the human activity [10]. As a further step, detail levels showing a high correlation with the typical environment vibrations have to be removed. Successively, the remaining components of the vertical acceleration signal has to be reassembled from the residual detail levels. The latter is expected to be really informative on possible seismic response of the structure. By comparing such residuals with pre-determined threshold, candidates anomalous seismic response of the structure can be highlighted.

3. Results and conclusions

In order to assess performances of the proposed methodology for implementing the early warning of structural behavior to seismic stimuli a dedicated experimental set-up has been used.

Actually, the multi-sensor node has been stimulated in the vertical direction by the acceleration signal provided by the shaker. The stimulating signal has been assembled from the concatenation of sinusoidal accelerations, at different amplitudes and frequencies, to mimic typical environment vibrations [10] and candidate seismic sources.

The time-frequency image shown in Fig. 2a, resulting from the wavelet coefficients computed on the vertical acceleration component recorded by the wireless multi-sensor node, highlights the applied mechanical solicitations.

Following the approach sketched in Fig.1c, such signal has been then decomposed in an approximation level and several details levels using the Discrete Wavelet Transform (DWT), with the Sym 8 mother wavelet. The obtained results are shown in Fig. 2b.

The next step requires the computation of the correlation factor between each detail level and the typical seismic and human generated amplitude/frequency patterns [10]. Detail levels showing a high correlation with the typical environment vibrations have been removed and the residual detail levels have been reassembled to produce the target signal. The new time-frequency image of the reassembled signal is show in Fig. 2c.

By comparing the wavelet coefficients of the reassembled signal, shown in Fig. 2c, with results in Fig. 2a, it is possible to observe that exogenous components provided through the shaker system have been significantly reduced, while meaningful components of the signal in the frequency band of seismic stimuli are clearly evincible.

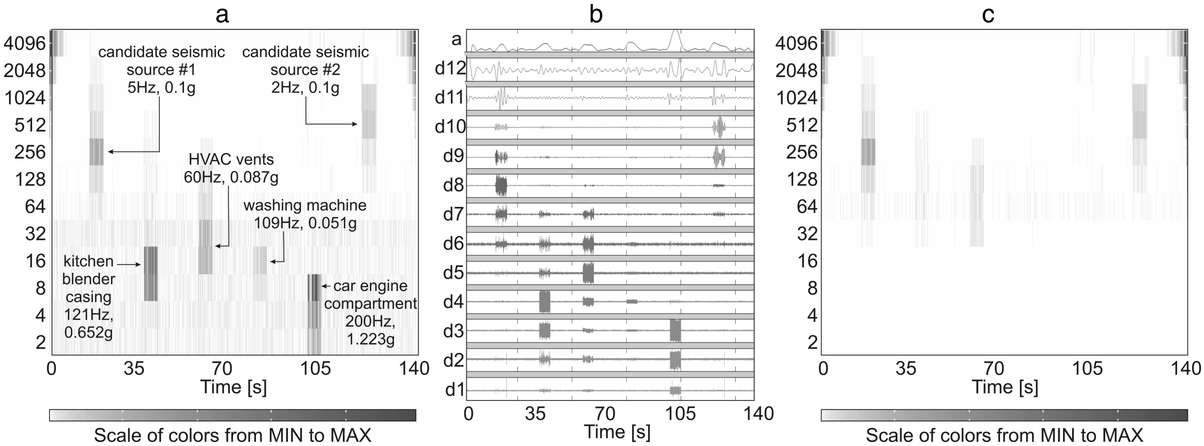

Fig. 2. (a) time-frequency image of the vertical acceleration signal acquired with the wireless multi-sensor node after the application of the mechanical solicitations; (b) discrete wavelet decomposition of the vertical acceleration signal with the Sym 8 mother wavelet; (c) time-frequency image computed on the reassembled vertical acceleration signal.

Results obtained by this preliminary experimental survey encourages future efforts for the development and the optimization of the proposed low cost multi-sensor strategy for early warning in structural monitoring. Main advantages of the strategy presented through this paper reside in the high spatial resolution and continuous operation of the monitoring system and the concrete possibility to isolate candidate anomalous behavior of the structure to seismic stimuli. These features are strictly correlated to the low cost multi-sensor architecture developed and the efficiency of the wavelet multiresolution paradigm adopted.

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