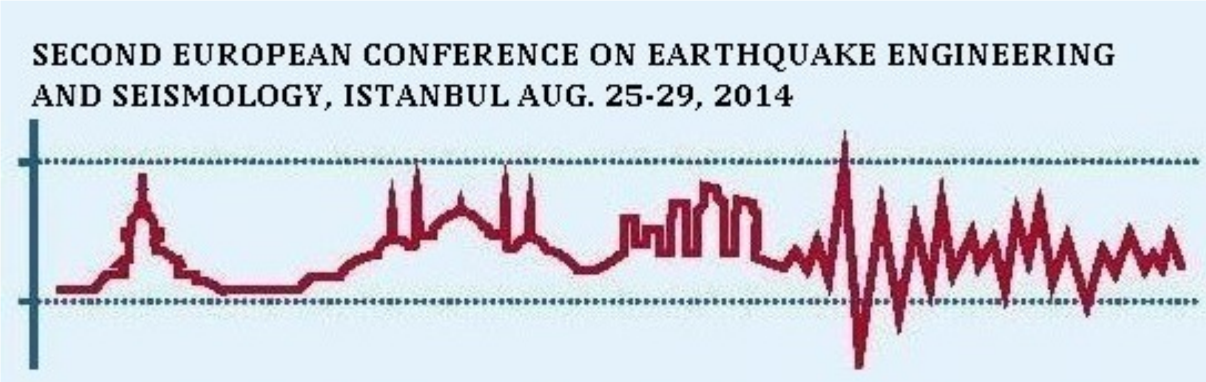

TOWARDS TO A PLATFORM OF MONITORING BASED IN WSN TO ESTIMATE THE STRUCTURAL HEALTH OF BUILDINGS

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ABSTRACT

This paper presents the primary results of the development of a structural low-cost monitoring platform based on wireless sensor networks to estimate the seismic risk of buildings. This platform will be able to estimate the structural vulnerability level of existing buildings. This platform has been called as SAVER (Structural Analysis of VulnerabilitiEs of buildings through wiReless sensor networks). The expected results in SAVER project intend to give the basis for the analysis of buildings and gather instrumental data that can be useful for decision-making of institutions and users that are responsible for infrastructure and buildings. Furthermore, in this project, we pretend to development and implement a new wireless sensor node. It is important to note, that this sensor node will be small size and low cost, capable of providing the necessary information to implement methods of vulnerability analysis and therefore, to estimate the seismic risk of buildings, such as hospitals or schools.

INTRODUCTION

Considering the impact of earthquakes on society (loss of life and property), it has been recognized around the world about the importance of mitigating the risk associated with this phenomenon. One of the strategies for mitigation is to have engineering construction industry that can withstand the effects brought about the earthquakes (Esteva, 1968). To avoid or reduce the consequences or the amount of damage caused by these events, the earthquake engineering provides criteria, methods and tools for structural design of such infrastructure, as well as testing, maintenance and reinforcement, if necessary, of existing buildings. Moreover, the margins of uncertainty that affect our ability to predict and characterize seismic intensity level is very high, this uncertainty affect our understanding of the relationship between the actual properties of the constructions (gravitational loads, stiffness and mechanical properties of the structure) and the assumed values in the structural design process. Rigorously, the above forces deal with these concepts within a framework based on probability analysis applied to seismic risk estimation.

For new buildings to be designed from design criteria described in the previous paragraph, it is achieved in a reasonable manner. However, for existing buildings there are several factors that can affect their performance against seismic events, namely: the age of the building, the absence of a

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structure maintenance program, the presence of damage and past seismic events occurred, among others.

As already said, one of the strategies to reduce the costs associated with losses in existing buildings due to earthquakes, is the use of methods and tools for evaluating their structural vulnerability (Ismael-Hernandez et *al*., 2013). For this purpose, methods for damage detection and structural monitoring systems based on sensors have been proposed and developed, recently. These systems have been mainly focused on structural health monitoring of bridges, tall buildings, dams and critical infrastructure (Ivanovic et *al*., 2000). Most of these systems use wired sensors instead of wireless sensors; this can difficult their deployment, especially in historic buildings. Another identified problem is related to the difficulty for end users to interpret and analyze information obtained from monitoring. In addition, the investment required to implement and operate these systems in most cases is very high, which limits their use to smaller buildings, but also important, such as hospitals, school buildings, and other public buildings. Indeed, in underdeveloped countries is very difficult to implement this kind of systems because of their cost.

For this reason, it is important to develop low-cost monitoring systems in order to estimate the structural vulnerability and deploy them on buildings such as schools, hospitals, among others.

RELATED WORK

In the literature we can find some studies that apply WSNs (Wireless Sensor Networks) in structural health monitoring. Among these, we find the work of (Kim, 2005). In this project Mica2 motes (UC Berkeley, 2004) are used to determine the structural health of the Golden Gate Bridge. Other works are focused on the structural health monitoring of offshore wind farms (Ping Wang, 2012). However, most jobs are oriented to the monitoring of large structures, i.e. bridges (Jeongyeup Paek, 2005), dams, etc. This allows us to claim that even today there are few efforts to monitor and determine the structural vulnerability of buildings such as those mentioned in previous paragraphs. Furthermore, many of the existing systems are focused on determining the health status of the buildings during a seismic event of considerable intensity. So, these systems are very useful for a post-seismic evaluation conditions for security and stability. Given the great advantages of having a structural monitoring system to determine some dynamic properties that have strong correlation with the structural responses, it is necessary to make efforts for the development of such systems.

The use of WSNs have brought several advantages in structural monitoring and the establishment of structural health compared to conventional methods where computers connected to accelerometers are used. In conventional methods, it is necessary to install cables through the structure, disturbing its normal operation and generating maintenance cost. Compared with conventional methods, WSNs provide the same functionality at a much lower price and a more flexible monitoring. Another problem is the high equipment and wiring installation and maintenance cost.

The cost of a conventional system with a computer and a piezoelectric accelerometer is about USD 40000 per sampling point. The estimated cost of the proposed system, in this work is less than USD 200 per point. In WSNs no wiring is required, making installation and maintenance much easier and inexpensive. Moreover, the use of WSNs allows SAVER platforms to be deployed and operate even if the building is in operation. It does not cause further visual impact due to its small size, low power consumption and installation flexibility. The advantage of structural health monitoring based on WSNs can be extended if the MEMS acceleration sensor type is used. The MEMS accelerometer is a silicon chip, which is very compact in size, low power consumption and cheap. Without MEMS, a small WSN, even low-power and low-cost accelerometer, would be degraded.

Thus, the SAVER platform will aim at gathering information to establish the vulnerability level of structural health of buildings. Such information will be used in decision making for both schemes and prevention programs, and for post-seismic evaluation.

The SAVER platform will be able to monitor and display information in real-time. It will determine from the implementation of several methods for estimating seismic response and damage detection, the level of structural vulnerability of buildings. In addition, our platform will offer several services that will notify users about potential risks of the structure through alarms, email and SMS. Besides, it will have a Web based monitoring platform and a mobile app for Android and I-Phone. Also, this platform will generate graphs, reports and statistics.

SAVER PLATFORM'S ARCHITECTURE

The SAVER platform will be composed of the following modules:

- **Data Analyzer:** This module transforms the data sent by the sensor network to international standard format (IS). Once data are transformed, they are stored in the Module Data Repository.
- **Data Repository:** It is a relational database server.
- **Structural Vulnerabilities Analyzer:** This is one of the most robust and important modules of the SAVER platform. It processes and analyses the records from the Data Repository module. Also, it has the function to estimate the degree of vulnerability.
- **WSN monitoring Mobile Application:** It is a mobile app that enables structural monitoring of buildings in real time. One of the most important features of this module is that it will notify the user on the structural vulnerability of monitored building.
- **Web based WSN monitoring platform:** It is a web-based platform that will allow real-time monitoring and visualization of acceleration sensors' parameters. This platform will provide the generation of statistics, graphs. It will display the parameters of the sensors and their position within the building. Likewise, it will allow the reporting and display of structural vulnerability level of buildings.
- **Notification System:** This module sends alerts about the building structure via e-mail and SMS. These notifications are critical in the case of a seismic event of considerable intensity.
- **Retrofit Rehabilitation Strategies:** Although this module is not part of the platform, it refers to the measures and recommendations to be made for the rehabilitation of the building, in case a high level of vulnerability was determined. This level is a result of the estimation made by the platform SAVER and corroborated by detailed methods.

Figure 1 shows the main modules of the monitoring platform of the SAVER project.

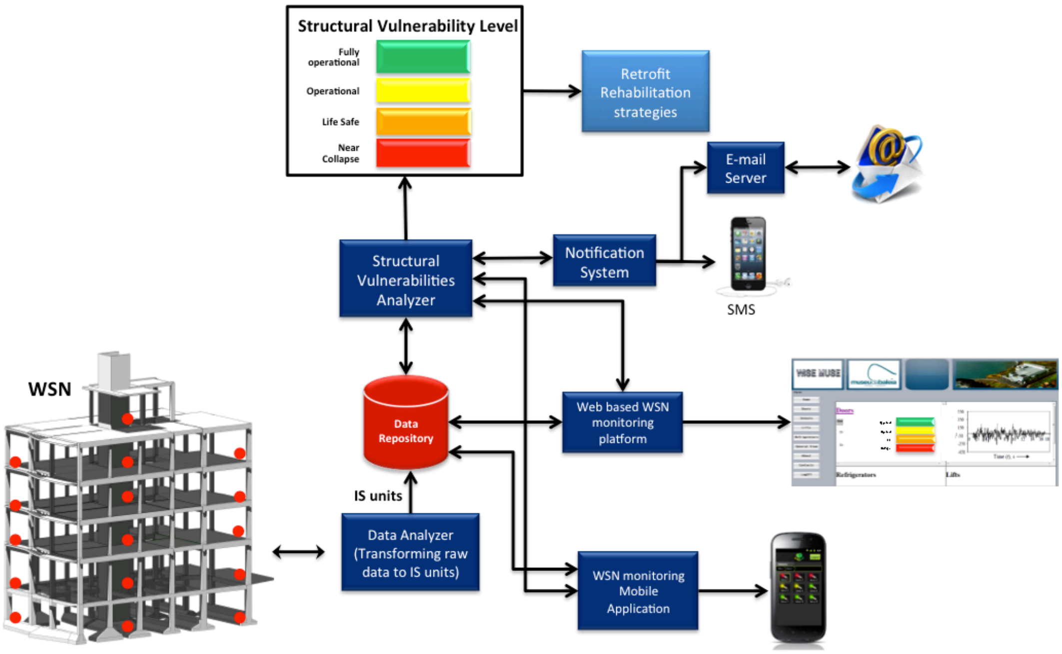


Figure 1. SAVER project's Architecture

DESIGN OF STRUCTURAL VULNERABILITIES ANALYZER MODULE

In Figure 2 the activities diagram of Structural Vulnerabilities Analyzer Module is shown. This figure shows the process to establish the structural vulnerability level. The structural vulnerability level will be associated with a damage level. The damage level can be estimated using a damage function similar to that proposed by Ismael-Hernandez et *al*. (2004). The function considers the physical damage at any story and is defined as:

$$d(u) = 1\text{-exp}(\text{-a}u^{m}) \qquad (1)$$

In this equation, a and m are parameters to be determined according with the structural system features (for example if the structural system includes frames, walls or a combination of this sub-systems); u is the local deformation of interest, normalized with respect to its peak value at failure (total loss). The damage function for the structural system is obtained as function of the corresponding interstory distortion (drift). In this way the parameter u is related to the lateral displacement. The damage function is continuous, for that reason the damage levels are given by an interval of values. The lateral displacement u can be determined considering two criteria: 1) using actual seismic records; and 2) using ambient vibration records.

The first approach is direct, because we use the record acceleration time history on different floors along the building. A double integration of the acceleration time-history can be used in order to obtain the response displacement. For this is necessary to apply a numerical procedure for integrating the corrected and filtered acceleration time-history, assuming that it has a linear variation between each time increment. For the velocity time-history this procedure is repeated in order to estimate the displacement time-history.

The maximum interstory average distortion can be determined by the following expression (Aldama, 2009):

$$\varphi_{maxj} = \left| \frac{u_{j+1}(t) - u_j(t)}{h_{j+1} - h_j} \right| \qquad (2)$$

Where φ_{maxj} is the maximum interstory distortion, $u_{\mathrm{j}}(t)$ is the lateral displacement at level "j" for a time t, and h_{j} is the vertical distance between each level.

Reyes (1999) and Meli and Reyes (2002), have shown that values of this parameter in several structural systems and non-structural elements, subjected to different stress level, may represent an acceptable damage indicator of the structure.

The second approach considers several steps that are described in the follow. First, it is necessary to synchronize the signals with a common time reference and carry out the polarization procedure according to the sensor´s orientation and the reference system. The baseline correction of the original records also is needed. In order to eliminate the undesirable components of frequency a signal filtering procedure is recommended for this we can use a Butterworth (Stearns and Hustt, 1990). For the ambient vibration records in three directions we can apply the Fast Fourier Transform (FFT), in order to obtain the Amplitude Fourier Spectra. With this information we can estimate the transfer functions, the vibration periods and mode shapes. The vibration period and the mode shapes can be used for generating a Simplified Reference System (SRS) using the criteria proposed by Ismael-Hernandez et *al*. (2004). The SRS has dynamic properties that represent the behavior of the actual building, however is necessary introduce the corresponding transform response factors. These factors are also defined in Ismael-Hernandez et *al*. (2004). In order to obtain the non-linear response of the SRS, in terms of lateral displacement, an adequate hysteretic model will be adopted. The non-linear responses can be related with a specified seismic scenario.

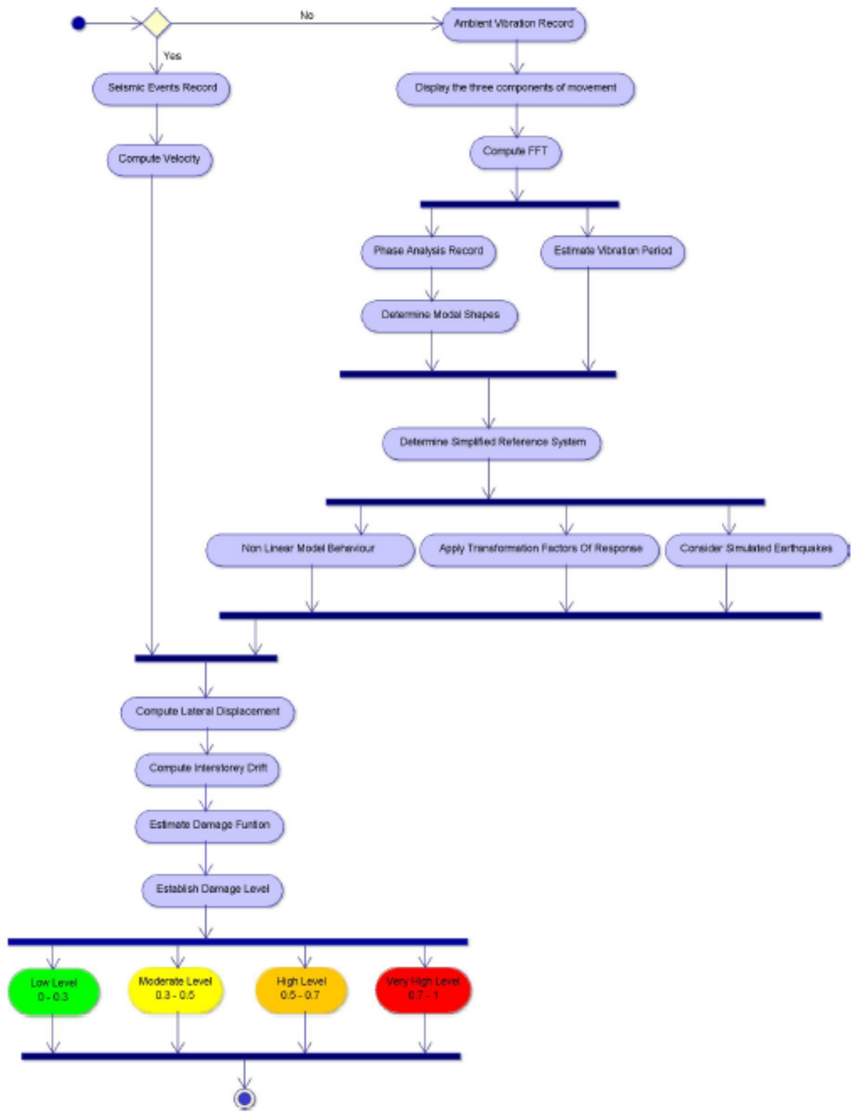


Figure 2. Activities diagram of the Structural vulnerability analyzer module

PRELIMINARY RESULTS

The preliminary results of the project SAVER are presented in this section. These results principally involve the assembly and configuration of the sensor node and the programming of the first stage of the Vulnerabilities Structural Analyzer module. The details of the preliminary results obtained so far are described in the following.

SAVER sensor node

Sensor nodes are responsible for the acquisition and transmission of data for further analysis and interpretation. These nodes are formed first by transducers, responsible for the acquisition of physical phenomena and their appropriate transformation to an electrical signal. This electrical signal is transmitted from node to node through radio frequency transmitters, Bluetooth, infrared or WI - FI, the first being the most used. A data acquisition board (DAQ) is the interface between the transducers and the radio transmitter, since it controls the acquisition by the transducer and the way in which they are transmitted to the radio transmitter. Given the network topology acquisition, sensor nodes behave as end points that transmit your information to any hubs or routers, which in turn relayed to a central computing element. A diagram of the topology of the sensor nodes and the router element are shown in Figure 3.

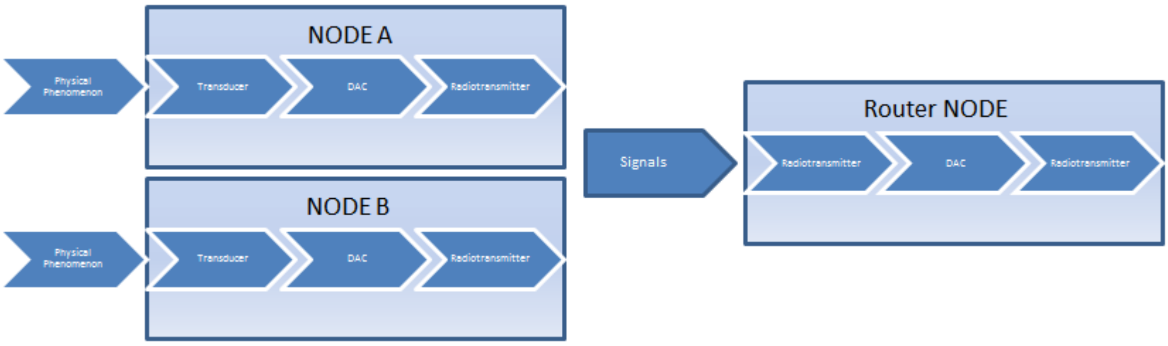


Figure 3. End Points represented in NODE A and B; retransmissions of signals to central computing element through Router NODE

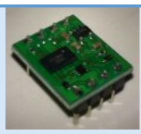
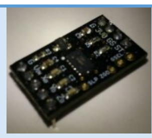
The transducers use acceleration sensors on the three axes (X, Y, Z). Currently, we are testing two series of sensors based on *Micro-electro-Mechanical Systems* (MEMS Technology; both are manufactured by Freescale Semiconductor. These sensors are mounted in two different boards that include the electronic components necessary for their proper operation. Thereby, the selected sensors are Freescale Semiconductor MMA7455L (Parallax Inc., 2008) mounted on a Parallax board (Parallax Inc., 2009), and Freescale Semiconductor MMA7361L (Freescale Semiconductor, Inc., 2008) mounted on a Modern Device MD0500 board (Modern Device, 2009). The MEMS technology operation can be understood as the analogy of suspended weight: when a force acts on it, it moves along the axis and it is detected and interpreted by electronic components.

The Data-Acquisition-Card (DAC) selected is the Arduino UNO platform (Arduino, 2013) mainly characterized for being an Open-source element and ability to form flexible hardware configurations, as well as being low-cost and programmable in C++ language; making it ideal for electronic prototypes.

Sensors

The selected sensors for the SAVER project have similar acceleration sensitivity features, on average from ±2 g to ±6 g, as well as low energy consumption and low profile. The main difference between them is the output type of the acceleration signal: analogue for the Modern Device module and digital for the Parallax module. The determination of which sensor presents better features such as acceleration sensitivity, fidelity of obtained data and easiness of calibration; will be by testing both sensors under the same operation conditions. In both sensors models, the output data resolution varies in accordance the acceleration range selected. For instance, under typical operation conditions, there is an 800 mV variation for each acceleration unit for the Modern Device module. A comparison of the main features of both sensors is presented in Table 1.

Table 1. Comparison of key features of the Parallax and Modern Device modules

Feature	Parallax Module	Modern Device Module
		
Sensor	MMA7455L	MMA7361L
Output Type	Digital (I^2C,SPI)	Analogue for each axis
Operation Voltage	3.6 – 5.0 V	3.6 – 5.0 V
Acceleration Sensitivity Ranges	±2.0 g, ±4.0 g, ±8.0 g	±1.5 g, ±6.0g

Bandwidth	62.5 Hz or 250 Hz	400 Hz for XY axes and 300 Hz for Z axis

Arduino UNO board

Arduino UNO platform is based in the microcontroller ATMega328. It has 14 pins of digital inputs and outputs and six pins for analogue inputs. The microcontroller is C++ programmable with the free Arduino software.

Although serial communication protocol is used for programming the Arduino board, the connection can be made through USB as the board has an USB-Serial chip converter. The power supply for the board is via USB; however, for applications were USB is unavailable, there is a jack for a DC power supply. The main components of the Arduino UNO board are showed in Figure 4. In table 2 presented the main features of the board.

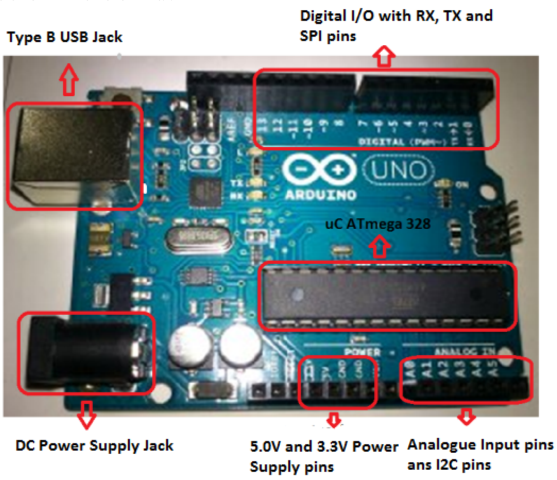


Figure 4. Arduino UNO board

Each of the analogue inputs have a resolution of 10 bits and a typical voltage of operation of five volts; thus, the voltage resolution for the analogue inputs is approximately $4.88\ {}^{mV}/_{bit}$. Thereby, there the board has an accurate reading resolution for an analogue sensor. As well, there are pins for different Serial communication protocols for digital sensors: UART (Universal Asynchronous Receiver/Transmitter), SPI (Serial Peripheral Interface) and I2C (Inter-Integrated Circuit).

Table 2. Main features of Arduino UNO board

Arduino UNO	
Microcontroller	ATmega 328
Typical Operation Voltage	5 V
Digital I/O	14 pins
Analogue Inputs	6 pins
Flash memory	32 kB
SRAM	2 kB
EEPROM	1 kB
Clock Rate	16 MHz

Link and power supply of components

The Arduino board is powered via USB from a computer at first instance. This setting is suitable due to changes and adjustments in the microcontroller program. The sensor modules are powered via voltage output pins from the Arduino board. The built-in circuitry on the module's boards allows a voltage supply of five volts instead of 3.6 volts.

The Serial communication protocol for programming the Arduino UNO is UART. Since Arduino is an open-source platform, drivers and software can be free downloaded directly from the Arduino web page (www.arduino.cc).

It is intended to test both sensors in a same node in order to compare their measurements under same operation conditions. Modern Device module will first be tested due simplicity of output signal (analogue). The magnitude of this signal is below five volts, so it can be directly connected to analogue inputs of the Arduino UNO board.

The output signal of the sensor module is a constant voltage value when it is static; i.e., the sensor is not affected by any acceleration. It is important to consider the final position of the sensor as it will show a acceleration on any of its axis due to gravity's force. This constant force will cause a misreading in the output signal and needs to be corrected in the calibration algorithm.

Structural Vulnerabilities Analyzer Module

Other preliminary result of the SAVER platform is the implementation of the Structural Vulnerabilities Analyzer module. This module is being implemented in Java using NetBeans IDE 7.1 (Oracle, 2013), this IDE allows the generation of acceleration graphics in three axes (X, Y, Z) from the data coming from the Data Repository module. Data extraction is performed in real time with updated within one second, using SQL statements. The acceleration data can be displayed with a range of up to 30 seconds. This data shows the acceleration of any sensor node connected to the system.

Currently, the graphical interface of the system is simple, as it only has to choose the node to be analyzed and the time interval you want to observe. Subsequently, more functions will be included. In this way, the system can display three acceleration components (see Figure 5), the first corresponds to the acceleration or north-south axis X, the second or East-West axis, the third axis vertical movement or Z. Besides, This interface includes a function called compute FFT (Fast Fourier Transform), which calculates the Fourier spectrum amplitudes by applying Fast Fourier Transform to the selected record of acceleration.

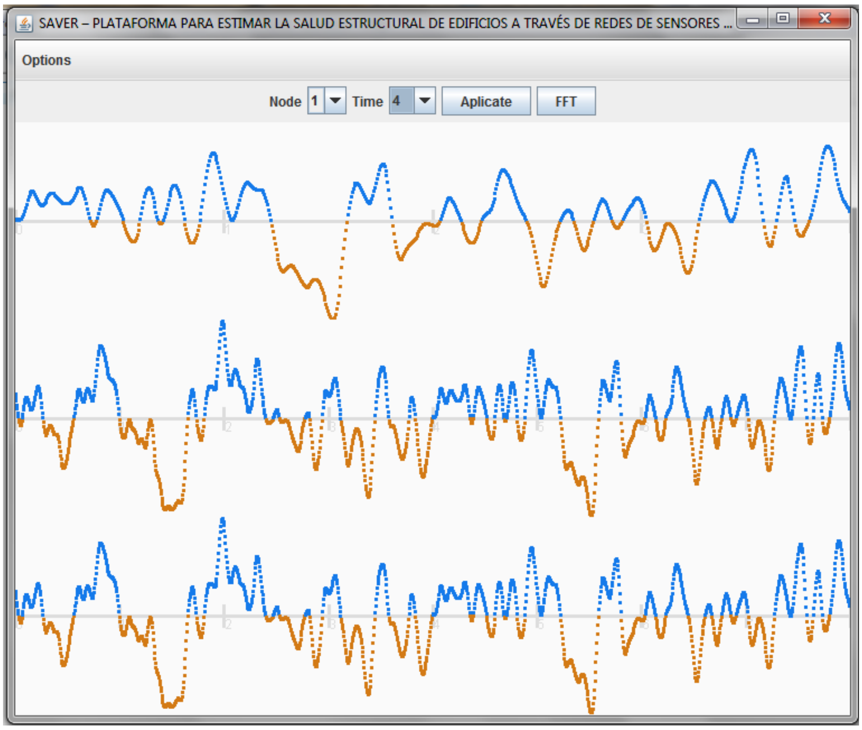


Figure 5. Graphical Interface of the Structural Vulnerabilities Analyzer module.

One of the most important functions of Structural Vulnerabilities Analyzer module is the use of the FFT that allows us to see more clearly which is the vibrating frequency of the analyzed structure. The system displays in a separate window the three graphs of FFT obtained from the accelerations data.

Currently, we are working on optimizing this module and implementing the transfer function among the sensor nodes. Thus, data produced by this function, can be analyzed and used to calculate the level of structural vulnerability of the building.

Data repository module

The database used in the SAVER project contains eight tables: data, featuresE, building, node, earthquakes, personal users and userType. Four tables belong to Data Analyzer module: data, featurese, node and earthquakes. And the other four contain useful information for the Web based monitoring platform, as shown in Figure 6.

Each table is used as follows:

- **Node:** Contains characteristics of the sensor nodes or electronic devices that send information captured by acceleration sensors
- **Data:** Stores the 3 different acceleration data of all sensor nodes, North-South, East-West, Up-Down, this information is temporary, which will last 1 week.
- **Earthquakes:** Stores the information when an earthquake occurs, storing the acceleration data in 3 axes, their corresponding sensor node data and information about the corresponding building structure.
- **Personal:** Saves the personal data of workers who have access to the system.
- **userType:** You can store different types of users, such as administrator, security guard or other necessary.
- **Users:** It is the relationship between personal and userType. It keeps the login and password for each person who can access the system.

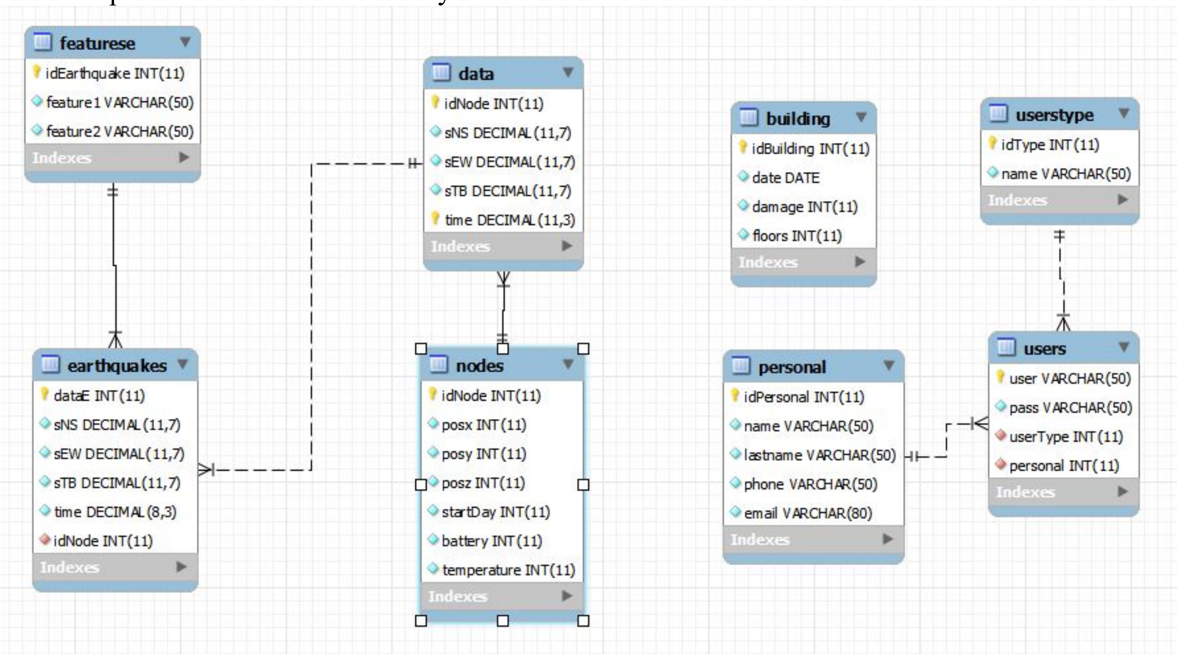


Figure 6: Database repository structure

Web based WSN Monitoring platform

The SAVER's Web monitoring platform has a restricted access to users. Each user has to be authenticated using username and password. It is estimated to have two types of users: one administrator and staff in general. The administrator will have access to the whole system. He/she can: i) create users; ii) delete users; iii) modify passwords; iv) analyze data obtained from ambient vibration; and; v) get the graphics acceleration and the FFT. The staff users will be able to visualize data in an easy and simple way, with a traffic light indicating the vulnerability level of the building. Also, they can visualize the sensor nodes state, verifying if they are working well. Finally, users can motorize the WSN. Figure 7 shows the first prototype of the SAVER Web platform.

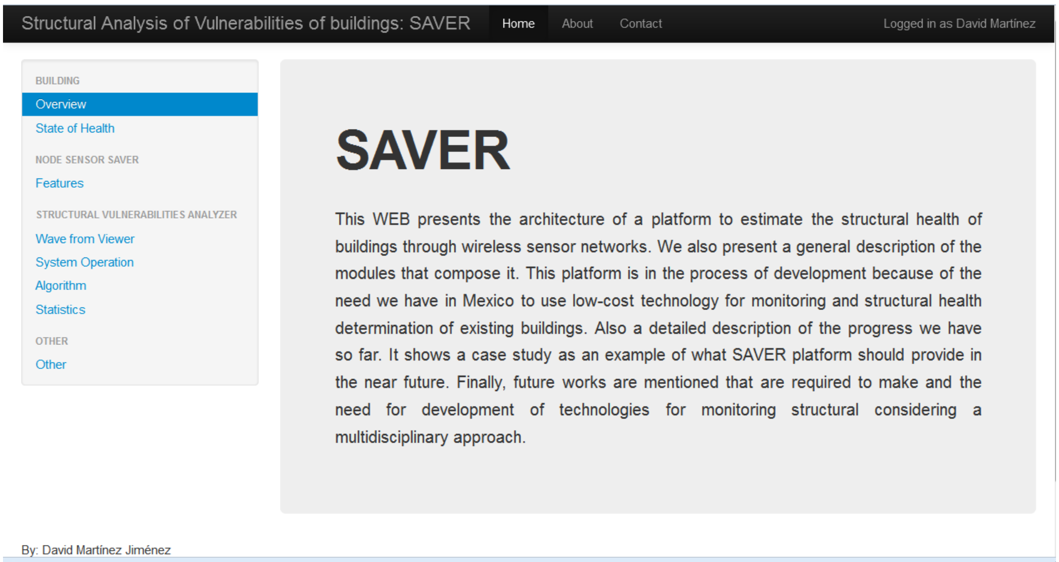


Figure 7. Homepage of the SAVER Web platform

CONCLUSIONS AND FUTURE WORK

This paper presents the SAVER project. This multidisciplinary project proposes a monitoring platform that aims at estimating the structural vulnerability of buildings through wireless sensor networks. This platform will offer a low-cost technology for monitoring and determining the structural health of buildings. The preliminary results of SAVER project, that have been obtained so far, were presented. In particular, the SAVER architecture, the sensor node, and the structural vulnerabilities analyzer module. This project provides two main advantages comparing to commercial solutions: i) a low-cost, not intrusive, and flexible monitoring system; and; ii) a platform to estimate the structural vulnerability and risk level. This has a paramount importance since, this platform will provide useful tools and information to increase knowledge and reduce uncertainty about the buildings' performance and behavior to seismic events. Thus, with this platform we can mitigate seismic risk in them.

Finally, the following steps (in short-term) of this research that are intended to carry out are:

- Testing the Parallax module using their two communication protocols (I2C and SPI) and decide which one best fits the requirements;
- Analyze different calibration algorithms and apply the best to the sensor node;
- To make a module where the sensor node can be protected against corrosive agents that may cause erroneous readings;
- To monitor the conditions in which the sensor node operates and make the necessary adjustments, whether in hardware (sensor node protection) or software (real-time correction of constants). In the first instance, we will monitor the temperature that can affect readings;
- In relation to the Structural Vulnerabilities Analyzer module is intended to extend its functionality and implement the transfer functions between the sensor nodes. Likewise, we intend to implement the remaining modules SAVER platform.

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