A Preventing Schema to Determinate Structural Damage in Buildings Caused by Earthquakes Using a Platform Based in Wireless Sensor Networks

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Abstract—**This paper presents a proposal to develop and implement analytical and technology tools for estimating the level of vulnerability of existing buildings. The proposed platform includes the design and implementation of a comprehensive structural monitoring platform based on wireless sensor networks. This platform is a low cost instrument capable of providing the necessary information to implement methods of response analysis and consequently improve structural damage detection. With the development of the system, we will be able to obtain practical criteria and automated functions, in order to estimate seismic structural vulnerability of existing buildings in a preventive way.**

Keywords-structural vulnerability; seismic events; wireless sensor networks; acceleration sensors.

I. INTRODUCTION

Considering the negative impact of earthquakes on society (loss of life and property), the importance of mitigating the risk associated with this phenomenon is recognized around the world. A strategy for reducing the risk of earthquakes involves buildings that can withstand the effects of the earthquakes [1]. To reduce the consequences or the amount of damage caused by these events, earthquake engineering provides criteria, methods, and tools for structural designs of such infrastructure. Additionally, earthquake engineering includes testing, maintenance, and reinforcement on existing buildings. The margins of uncertainty that affect our ability to predict and characterize seismic intensity level are very high. This uncertainty affects 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. The above forces deal rigorously with these concepts within a framework based on probability analysis applied to seismic risk estimation.

New buildings are generally designed and built following the aforementioned design criteria. 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 structural maintenance program, the presence of damage due to past earthquakes, among others.

Therefore, the development and implementation of methods and tools for the structural vulnerability assessment can be considered as useful strategy to reduce the costs associated with losses in existing buildings due to earthquakes [2]. For this purpose, methods for damage detection and structural monitoring systems based on sensors have been proposed and developed recently. These systems have been focused mainly on structural health monitoring of bridges, tall buildings, dams and critical infrastructure [3]. Most of these systems use wired sensors instead of wireless sensors; this can hinder their deployment, especially in historical 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 and public buildings such as hospitals, school buildings, etc. In developing countries, it is very difficult to implement these types 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.

This paper is organized as follows. Section II includes a descriptions of related work. Section III presents the SAVER Web-based monitoring platform and a detailed description of the structural vulnerability module. Section IV briefly presents the SAVER sensor node. Section V presents the modeling and deployment of an application example of the SAVER project. Finally, section VI provides some conclusions and future work perspectives.

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II. RELATED WORKS

Structural Health Monitoring (SHM) systems are emerging tools to help engineers improve the safety and maintainability of critical and conventional structures. SHM combines a variety of sensing technologies with an embedded measurement controller to capture, log, and analyze real-time data. SHM systems are designed to reliably monitor and test the health and performance of structures. Most of the existing solutions of SHM systems around the world employ movement-sensing devices, like accelerometers, but the majority studies use wired networks. In addition, most of them are used for detecting only one parameter correlated with the damage level and this is typically the inter-story drift. This parameter is enough to evaluate the performance given the occurrence of an earthquake; it means that is useful for evaluating the post-earthquake condition. But the problem arises when we need to evaluate the performance or vulnerability condition before an earthquake. In this case we need more information and the drift is not enough, because we also need to generate a model and obtaining the non-linear response for the structural system.

On the other hand, in the literature we can find some studies that apply to Wireless Sensor Networks (WSNs) for structural health monitoring. Among these, we find the work of Kim [4]. In this project, Mica2 motes [5] are used to determine the structural health of the Golden Gate Bridge located in San Francisco CA. Other works are focused on the structural health monitoring of offshore wind turbines [6]. However, most studies are oriented to the monitoring of large structures, i.e., bridges [7][8], dams, etc. This allows us to claim that currently there are few efforts to monitor and determine the structural vulnerability of buildings. Furthermore, many of the existing systems are focused on determining the health status of the buildings during an earthquake event with considerable intensity.These systems are very useful for a post-seismic evaluation conditions, 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. Other disadvantages are low efficiency, high cost, inflexibility and disturbance. Another problem is the high equipment and wiring installation and maintenance cost. Compared with conventional methods, WSNs provide the same functionality at a much lower price and more flexible monitoring. Other advantages are high efficiency, flexibility, reliability, and scalability. WSNs are not easy to be disturbed by operation equipment and can facilitate efficient distributed data processing and real time damage detection [8].

The cost of a conventional system with a computer and a force-balanced accelerometer is about USD 20000 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. More so, the use of WSNs allows SAVER platform 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 Micro-Electro-Mechanical Systems (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 Structural Analysis of Vulnerabilities of Buildings through Wireless Sensor Networks (SAVER) project aims at gathering information to establish the structural vulnerability level of buildings. Such information will be used in decision making for two schemes: prevention programs, and post-seismic evaluation. As mentioned before, knowing the structural vulnerability or seismic risk level of a specific building could be useful for the owner, because he or she can implement retrofit strategies on the building in order to recover its structural health condition and avoiding possible collapse, structural damage or injuries from users in case of a future earthquake.

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. A complete description of SAVER project's architecture can be found in [9].

III. WEB BASED WSN MONITORING PLATFORM

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 IOS. Also, this platform will generate graphs, reports and statistics. Some preliminary results of the SAVER project was published in [9].

The SAVER Web-based platform provides a building's structural vulnerability analysis, of the different sensors inside each building. These reports provide information like the power supply and the time capture of each parameter [10].

The preliminary results of the SAVER project are presented in this section. These results principally involve the assembly, setup and configuration of a wireless sensor network including the sensor node.

The details of the results obtained so far are described in the following sections.

A. Database description

For proper operation, nine main tables are handled, which have the necessary information to control the sensors parameters: *Building, Sensor Acceleration, Sensor*

TempHum, Node, Cluster, Seism, Acceleration Amplitude, User and *Scenarios.*

For each building, we store its structure information, its features, its location, as well as the location of the nodes inside it. Also we store data of clusters, where a cluster is composed by a set of nodes. It is important to note that a building can be cover by one or more clusters. Each node contains four kinds of sensors: one of them is an Acceleration Sensor which records three-axial acceleration movement (longitudinal, transversal and vertical), Temperature, Humidity Sensors that record the ambient temperature and humidity, respectively, and a GPS sensor.

This data is used to establish when an earthquake occurs by overcoming the condition of an acceleration threshold and after this happens; we store the date, time, maximum amplitude, and the acceleration and frequency amplitude for each axis. All of these are used to calculate the Fourier spectrum in terms of frequency (Figure 1).

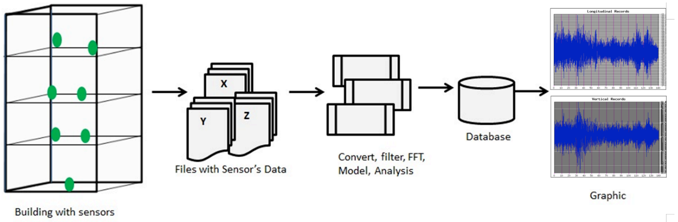


Figure 1. Flow of the process.

The description of the tables is detailed as following:

- *SensorAcceleration*: It stores the longitudinal, transversal and vertical records from Acceleration Sensor.
- *Sensor TempHum*: It stores the temperature and humidity that occurs in the environment at a specific time.
- *Node*: It stores the ID of each node, as well as the Acceleration Sensor ID, the Temperature and Humidity Sensor ID, the cluster where the node belongs and the localization where the node is placed on the building.
- *Cluster*: Here, the cluster ID and its location are stored.
- *Building*: Here we can store the building´s geometry, blueprint per floor in which is showed the location of each node, name, use, address, state, country, latitude, longitude, topography, foundation type, building support type of "x" and "y" axis.
- *Acceleration Amplitude*: It contains many acceleration amplitudes and Fourier spectrum of the records.
- *User*: It stores the username, password, type of user, name, last name, telephone and email of the system users.
- *Scenarios*: It stores pictures of the building, floor and room where the sensors are placed.

The SAVER database design is shown in Figure 2.

The "Home" section includes a brief description of the project, while the "Building" section is able to display the plans and basic information of each building (Figure 3). The WSN section shows the topology of the network, including its description and real-time location of each sensor inside the building. The Structural Vulnerability System (SVS) section will provide the generation of vulnerability reports, in order to consult the building's structural health and establish its possible rehabilitation strategies. As an example, Figure 4 shows the graphs of the longitudinal, transverse and vertical ambient vibration records captured each 0.005 seconds at UPAEP High School.

B. *Structural Vulnerability module*

To evaluate the structural vulnerability we can use a diagram as the shown in Figure 5. This procedure was originally proposed by Rodríguez Peralta et al. [9] and shows the process to establish the structural vulnerability level. This level will be associated with a structural damage parameter, u. In structural engineering is very well known that damage level can be estimated using a function defined as:

$$d(u) = 1 - \exp(-au^m) \tag{1}$$

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 inter-story 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 advantage of our approach is that the lateral displacement u can be determined considering two criteria: 1) using actual seismic records (as similar existing systems work for giving a post-event structural health condition); and 2) using ambient vibration records (that it is the novelty in this project). For that reason, in this paper we focus on the second criterion, details for the former can be found in [9].

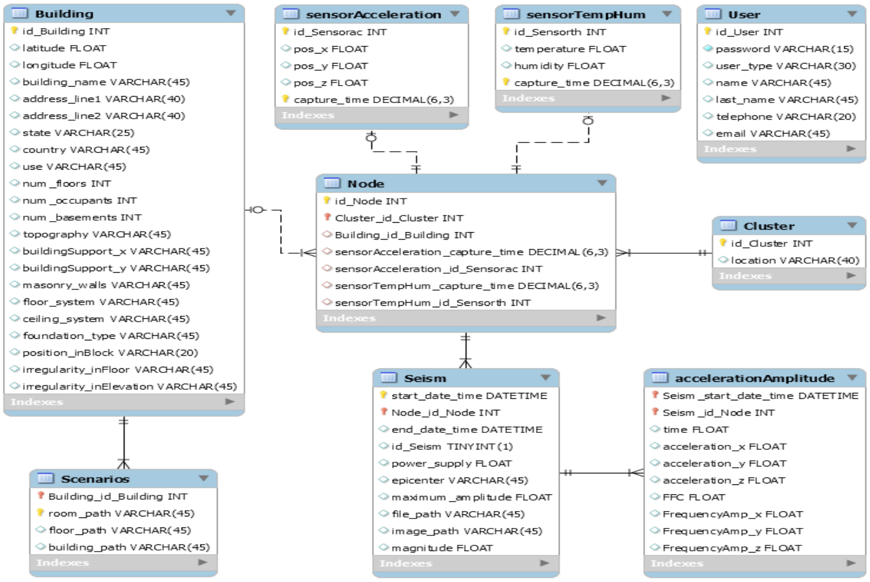


Figure 2. SAVER Database schema.

The second approach, based on ambient vibration records, can be used to perform modal analysis and generates simplified structural models. These models are necessary for carry out the non-linear analysis and getting the parameter u. The approach considers several steps, which are described in the follow (Figure 5). i) 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. ii) The baseline correction of the original records also is needed. iii) In order to eliminate the undesirable components of frequency a signal filtering procedure is recommended for this, we can use a Butterworth filter. iv) For the ambient vibration records, previously corrected in three directions, we can apply the Fast Fourier Transform (FFT), in order to obtain the Amplitude Fourier Spectra. v) With this information (Amplitude Fourier Spectra) we can estimate the transfer functions, as well as the vibration periods and modal shapes (modal analysis). vi) The vibration period and the modal shapes can be used for generating a Simplified Reference System (SRS) using the criteria proposed by Ismael-Hernández et al. [11]. The SRS has dynamic properties that represent the behavior of the building, however, it is necessary to introduce the corresponding transform response factors. These factors are also defined in [11]. In order to obtain the non-linear response of the SRS, in terms of lateral displacement, an adequate hysteresis model will be adopted. vii) The non-linear responses can be related with a specified seismic scenario, in this step the accelerogram (actual or synthetic) is defined. viii) The non-linear response analysis on the SRS is carried out and the parameter u is estimated. ix) The damage function, given by Equation 1, is evaluated considering the u value. x) Finally, the damage level is established and classified. It is important to mention that we can use the second approach to verify the structural health condition for future seismic scenarios, thus SAVER project aims to evaluate the vulnerability previous the occurrence of an earthquake. So far, no similar system with this capability exists.

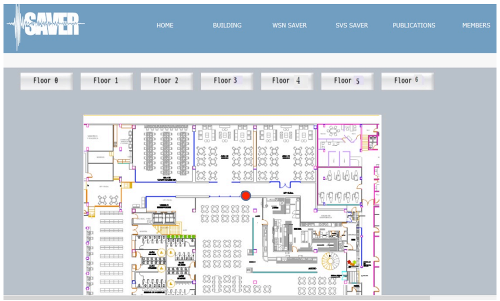


Figure 3. Section “Building”.

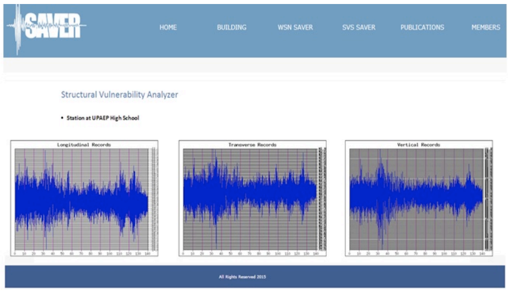


Figure 4. Section “SVS”.

IV. SAVER SENSOR NODE

The sensor node is responsible for the acquisition and transmission of data for further analysis and interpretation. The node gets Acceleration (vibration) in the three axes (X, Y and Z) from the surface where the node is mounted.

The measurement signals are sent to a Microcontroller where they are processed. This is in order to interpret and to make necessary adjustments to the data. Then, the data is sent via radio-frequency devices to other sensor nodes.

The data acquired for the sensor is 12 bits information that include acceleration in 3 axes and internal temperature.

A. Prototype

The SAVER prototype consists of an Arduino UNO micro-controller that is attached with a Xbee shield. The Uno is a microcontroller board based on the ATmega328P. It has 14 digital input/output pins, 6 analog inputs, a USB connection, a power jack, an ICSP header and a reset button [12]. The micro-controller is attached with a Pololu module that contains a LSM303D accelerometer, voltage regulator, and a temperature sensor. The radio is a Xbee pro S2B operating in 2.4GHz [13], based on the range regulated by NOM-121-SCT1-2009 in the Mexican territory. To communicate with the sensor, we use SPI and Zigbee protocol.

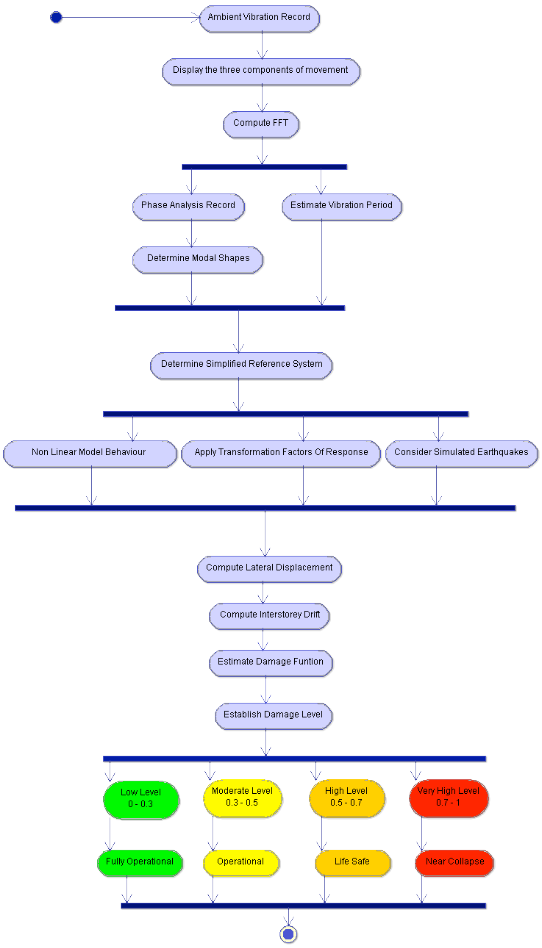


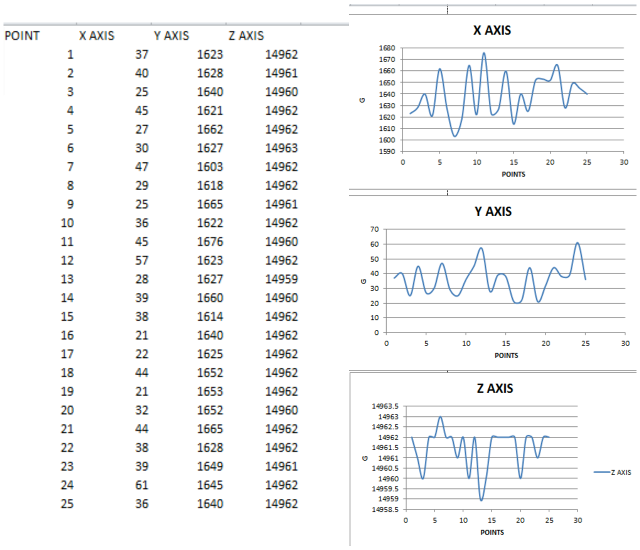
Figure 5. Activities diagram to evaluate the Structural Vulnerability Level.

The LSM303D is a 3D digital linear acceleration sensor and a 3D digital magnetic sensor. The LSM303D includes an I2C serial bus interface that supports 100 kHz and 400 kHz in SPI serial standard interface. The measurement ranges are ± 2, 4, 6, 8, 16 g, for SAVER node the specific range is ±2g with a sensitivity of 0.061 mg/LSB. The energy demand of the LSM303D is 300 µA with a linear acceleration sensitivity change consumption vs. temperature of ±0.01% ºC tested based on 25ºC. The module has two advantages for the node. The first is the internal temperature sensor that gives the information every period of time and the second is the self-test option. When self-test is activated, the device output level is given by the algebraic sum of the signals produced by the acceleration acting on the sensor and by the electrostatic test-force [14]. The frequency programmed for the sensor is 100 samples per second according to seismic requirements.

In Figure 6, the final prototype is shown and includes one accelerometer and a temperature/humidity sensor.

The node was tested via PYTHON interface to log the collected data in a .txt file and to graph the force applied to each axis. With a baud rate of 9600 bauds-per-second (bps), the Arduino board acquires data in binary and then processes it to transform in g data. The resolution used was ±2 g with and Analog-Digital Converter (ADC) of 16 bits, meaning it is expected a number within ±32,767, which are max/min absolute values of the sensor. Figure 7 shows the PYTHON interface and the acquired data.

Figure 6. Final prototype of SAVER sensor node.



POINT	X AXIS	Y AXIS	Z AXIS
1	37	1623	14962
2	40	1628	14961
3	25	1640	14960
4	45	1621	14962
5	27	1662	14962
6	30	1627	14963
7	47	1603	14962
8	29	1618	14962
9	25	1665	14961
10	36	1622	14962
11	45	1676	14960
12	57	1623	14962
13	28	1627	14959
14	39	1660	14960
15	38	1614	14962
16	21	1640	14962
17	22	1625	14962
18	44	1652	14962
19	21	1653	14962
20	32	1652	14960
21	44	1665	14962
22	38	1628	14962
23	39	1649	14961
24	61	1645	14962
25	36	1640	14962

Figure 7. PYTHON Interface and Acquired Data from SAVER Sensor node.

Free Digi software, XCTU [15] is used to configure the radio devices.

In the test presented herein, devices are in factory defaults. The working cluster is presented in Figure 8.

Figure 9 shows the data obtained in each of the elements of the network. Data is observed using the serial monitor Arduino IDE. LSM303D accelerometers are connected to the End Devices. Those components obtain values corresponding to the X, Y, Z axes. Window COM4 shows the data obtained from an end device. This data is sent to the router (window COM6), which will forward it to the coordinator. Due to the coordinator is set in API mode, values obtained for it are represented in hexadecimal format. They are displayed in the window COM8. Ech column contains data of X, Y, Z axis respectively, and the Router address.

V. WSN DEPLOYMENT IN A BUILDING

The expected results, in SAVER project, intend to give the basis for the analysis of buildings and gather instrumental data that can provide the necessary information to implement methods of vulnerability analysis and therefore, to estimate the seismic risk of buildings, such as hospitals or schools.

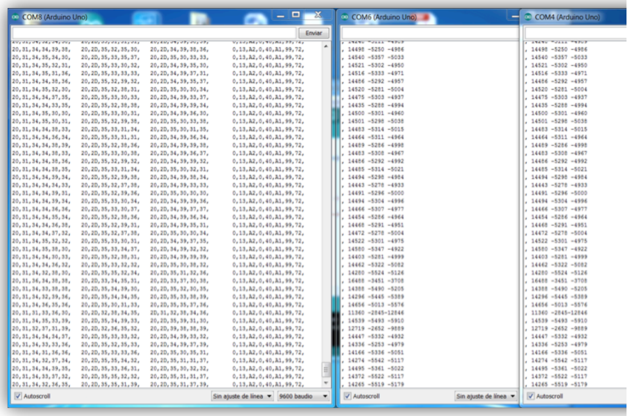
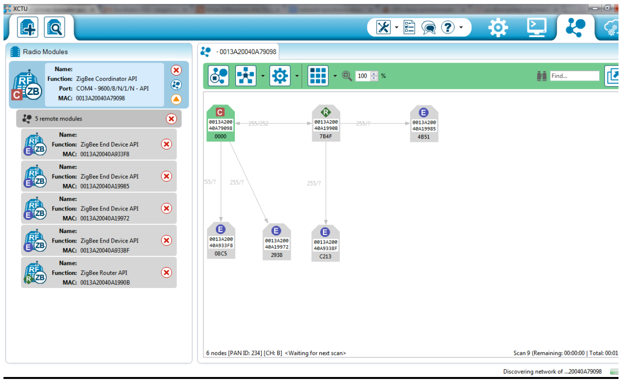


Figure 8. Data from the Coordinator, Router and End Device (Sensor Node) displayed on the Serial Monitor Software Arduino IDE.



Name:
Function: ZigBee Coordinator API
Port: COM4 - 9600/8/N/1/N - API
MAC: 0013A20040A79098

5 remote modules

Name:
Function: ZigBee End Device API
MAC: 0013A20040A933F8

Name:
Function: ZigBee End Device API
MAC: 0013A20040A19985

Name:
Function: ZigBee End Device API
MAC: 0013A20040A19972

Name:
Function: ZigBee End Device API
MAC: 0013A20040A9338F

Name:
Function: ZigBee Router API
MAC: 0013A20040A1990B

0013A200 40A79098 0000
0013A200 40A1990B 7B4F
0013A200 40A19985 4B51
0013A200 40A933F8 08C5
0013A200 40A19972 2938
0013A200 40A9338F C213

6 nodes [PAN ID: 234] [CH: B] <Waiting for next scan>
Scan 9 (Remaining: 00:00:00 | Total: 00:01

Discovering network of ...20040A79098

Figure 9. Cluster including: 1 Coordinator, 1 Router and 4 Sensor Nodes.

SAVER project will be validated in the building T that is located in the Central Campus of UPAEP University, Puebla City Mexico, and was built in 2007. The plan of the building has a rectangular geometry with dimensions 24 x 35 m. The building has six levels with a height of 3.15 m each one; the total height is around 19 m. The building does not have regular configuration in plan and elevation; because it presents openings and overturning along its height. The use of the building is mixed, there are two restaurants, twelve lecture rooms, a computer room, three meeting rooms, and several office areas and twelve classrooms. The structural system is based on steel resisting-moment frames (columns and beams). Some columns have circular cross sections and the other have squared cross section. The beams are based on W standard shapes. The floor systems are based on thin composite steel-concrete with 0.12 m thickness. The non-structural elements (internal walls) are based on drywalls with 0.10 m thickness. The external walls are based on masonry with 0.15 m thickness. The predominant material on the facade is glass. Figure 10 shows a view of the WSN in building T.

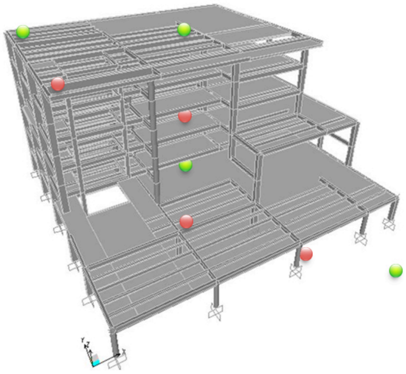
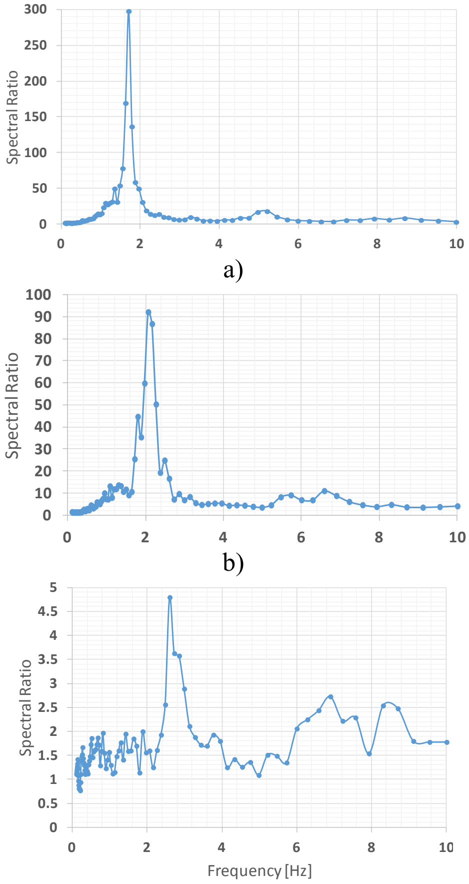


Figure 10. Lateral view of the WSN in the building T.

Ambient vibration records in three points were obtained on the building, P01 and P02, which correspond to the geometric centroid and the corner at the roof of the building, respectively; P03 corresponds to the geometric centroid at the ground floor of the building. For each point four records were taken considering 15 minutes. A tri-axial forced balanced accelerometer (Kinemetrics Basalt Accelerometer) was used as an instrument for obtaining the records (Figure 11). In this stage of our study we only present the modal analysis using the Basalt Accelerometer, we are working to implement our sensors in order to present a comparison between them.

The procedure for modal analysis presented in Figure 11 is summarized in the following lines. Frequencies and periods were determined for the first three modes: longitudinal (L), transversal (T) and rotational (R). For this, a computer program GEOPSY [16] was used in order to obtain the Amplitude Fourier Spectrum (AFS) for each record, in this way, the horizontal components of the movement (longitudinal and transversal) are only considered for computing the spectral ratios. The procedure for each of the mode is described below. Longitudinal mode (L), the numerator corresponds to the AFS in the longitudinal component obtained in the geometrical centroid at the roof level, and the denominator corresponds to the AFS in the longitudinal component obtained in the geometrical centroid at the ground floor. A similar procedure was used for transversal and rotational modes.



a)

b)

c)

Figure 11. Spectral ratios estimated for the building using ambient vibration and a forced balanced accelerometer; a) Longitudinal mode, b) Transversal mode, and c) Rotational mode.

VI. CONCLUSION AND FUTURE WORK

This paper presented the SAVER project. This multidisciplinary project proposes a monitoring platform that aims at estimating the structural vulnerability and preliminary seismic risk level 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, (i) the SAVER architecture, (ii) the sensor node, (iii) Web platform, and (iv) 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 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 buildings.

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

- Test mBed boards to compare manageability with the sensors.
- Compare and implement different accelerometers sensors and test humidity in locations where SAVER nodes will be located.
- Implement SAVER sensor network and test under worst-case scenario conditions.
- 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. Develop and implement the models using simplified reference systems.

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