MQTT based event detection system for structural health monitoring of buildings

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Abstract. Structural Health Monitoring (SHM) consists in a fundamental research field which aim to evaluate the current status of an infrastructure with the main purpose to identify damages and prevent catastrophic events. This paper presents an SHM solution that implements an automatic system based on the MQTT protocol and IoT devices for detecting seismic events. In particular, the architecture consists of a set of accelerometer sensors which communicate by means of a decentralized network topology (i.e., an Ad hoc Network configuration). Moreover, the system has the capacity to transmit the information about the events detected in real-time using cloud services. In order to verify the proper operation, the system was deployed on an actual building and the information acquired by the sensors was registered along four months. In this context, a relevant event detected was selected for analyzing the dynamic response of the building during a seism. Results show that the acceleration values increase as a function of the building height. Regarding the seismic event analyzed, the RMS values of acceleration identified on the basement were 0.26, 0.22, and 0.22 cm/s^2 and in the case of the eighth floor were 1.18, 1.33, and 0.59 cm/s^2 for the longitudinal, transverse, and vertical axes, respectively. Additionally, a first assessment regarding the structural health status of the building was performed through the OMA methodology (Operational Modal Analysis). Specifically, the FDD (Frequency Domain Decomposition) mechanism was used to determine the first four frequencies and its respective vibration modes.

Keywords: MQTT, IoT, Event detection, WSN, Structural Health, Operational Modal Analysis.

1 Introduction

Structural Health Monitoring (SHM) consists in a crucial research field which aim to evaluate the current status of an infrastructure (e.g., bridges, heritage buildings, and strategic facilities, among others). This analysis is performed with the main purpose to identify damages and prevent catastrophic events. In particular, there are two methodologies developed in order to characterize the dynamic response of structural elements which are known as Experimental Modal Analysis (EMA) and Operational Modal Analysis (OMA), [1]. The EMA strategy is based in the application of artificial sources (e.g., controlled explosions or the use of instrumentation such as a vibrating table) therefore this methodology is usually applied in a laboratory environment. On the other hand, OMA is carried out under the natural conditions which structures are exposed daily (i.e., seismic events or the load conditions), [2].

Furthermore, the OMA strategy involves deploying a set of sensors (e.g., accelerometers) along the structure under analysis. Consequently, the number and the proper location of the sensors are the main factors to take into account, as is discussed in [3]. In this context, in [4] and [5] are presented studies where is proposed the use of triaxial accelerometers in order to evaluate the modal parameters of buildings. In particular, the authors point out that through the vertical component it is feasible to register the phenomena of rocking. In addition, the authors propose the installation of sensors located parallel to each other with the aim to identify torsional modes.

Following with this methodology, with respect to the data captured by the sensors, it is necessary to ensure the continuous register of the information. Currently, this challenge can be faced through emerging technologies such as Internet of Things (IoT) and Wireless Sensor Networks (WSN). For example, in [6] is described an SHM architecture that incorporates IoT technologies with the purpose to determine structural damages as well as in order to generate warning messages. A similar study is described in [7], in this case, the proposal includes three functional layers, data acquisition, information management, and SHM services. Moreover, in [8], the authors propose a system based on IoT for structural health monitoring in real-time. Finally, in [9] is presented a study that incorporates both IoT and WSN technologies in order to deploy an early warning system.

Regarding WSN it is worth mentioning that technology consists in a specialized application of the communication paradigm known as Ad hoc Networks. That sort of network has the capacity to self-configuring without the need of a central station or a preexisting infrastructure, that represents a valuable feature, particularly during critical conditions where the conventional communication networks can be affected. For example, in [10] a resilient communications system based on Ad hoc Networks is proposed as alternative for emergency conditions after natural disasters. Additionally, in [11] the authors propose the application of Mobile Ad hoc Networks (MANET) on different emergency scenarios. In [12] a similar work is presented, but in this case, the study focuses on disaster scenarios caused by seismic events.

On the other hand, regarding the management of sensor devices used in SHM systems, the MQTT protocol (Message Queue Telemetry Transport) represents an efficient and current mechanism characterized by a simple design, high level of security, low bandwidth requirement, among others advantages [13], [14]. The MQTT operation is based on a publish-subscribe schema where the information is organized in a hierarchy of topics.

In such a context, in [15] is described a proposal for detecting natural disasters, particularly, the MQTT client functionality was implemented on a Raspberry Pi platform while the server operation was configured on a computer. Additionally, in [16] the authors propose a solution based on the MQTT that takes advantage of the sensors available on smartphones for deploying an early warning system focused on seismic events. Also, in [17] is described a study for monitoring the status of a building by means of an accelerometer that publishes the information captured through an MQTT topic

In particular, seismic events are the main scenario to consider during the implementation of an SHM system. In that sense, there are various mechanisms in order to detect a seism, which differ on complexity and computational cost. For example, the most basic technique consists in analyzing if the amplitude of seismic signals exceeds a certain threshold value. Another algorithm widely used is the STA/LTA mechanism (Short Term Average to Long Term Average), which computes the moving average of the signal amplitude using a short and a long-time window. The short time window (STA) allows for detecting seismic events while the long window (LTA) provides information about the seismic noise. Consequently, when the STA/LTA relation exceeds a threshold value, this behavior is considered as the start of a seismic event [18]. In such a context, in [19] and [20] the authors propose algorithms based on STA/LTA with the purpose to identify specifically the P-wave (primary wave). It is worth indicating that there are other variants of this algorithm, for example, the mechanisms Carl STA/LTA, Delayed STA/LTA and Recursive STA/LTA, where this later variant presents higher computational efficiency and smoother response, as is discussed in [21] and [22].

Additional techniques for detecting seismic events are described in the literature. For example, in [23] is proposed a solution based on Convolutional Neural Networks. On the other hand, in [24], the authors present a mechanism using deep-learning techniques. Finally, in [25] is detailed an adaptive mechanism for detecting seismic events considering the conditions of environmental noise.

In such a context, with the aim of evaluating the structural status of buildings that can be affected by environmental conditions (i.e., earthquakes), this paper proposes a solution for deploying a remote SHM architecture that incorporates emerging technologies. Particularly, WSN, IoT as well as an automatic mechanism for detecting seismic events that is based on the MQTT protocol.

The main contributions of this work compared with related works, are the capacity for analyzing events in real-time, the extraction and transmission only of data related to the events that result in a reduction of the bandwidth demand and consequently an improvement with respect to the delay in the communication system.

Moreover, with the purpose of deploying a resilient system, the accelerograph stations communicate through a multi-hop Ad hoc wireless network configured along a real scenario. Results show that the proposed system operates successfully and allows for characterizing the dynamic response of a building to seismic events.

The rest of the paper is organized as follows. In Section 2, the methodology and components are detailed. The experiments and results are discussed in Section 3. Finally, in Section 4, the main conclusions of this proposal are presented.

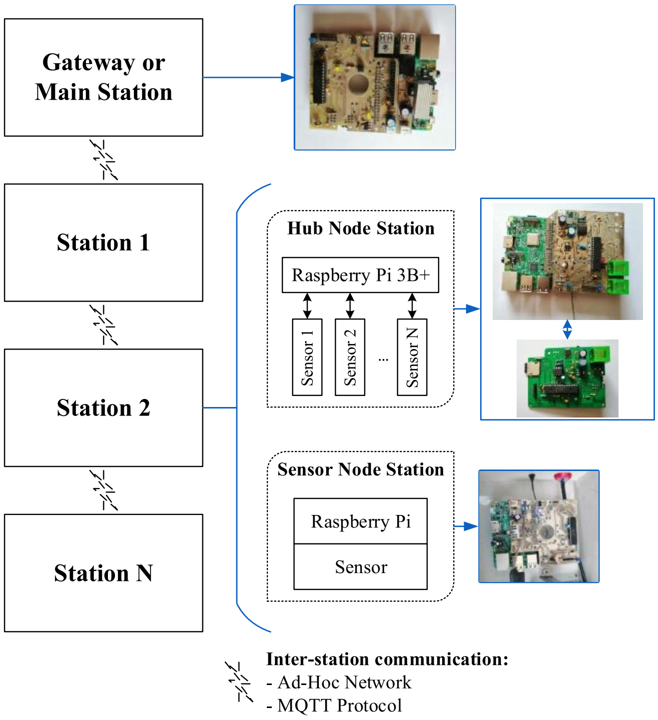

Fig. 1. Architecture of the SHM system.

2 Methodology and Components

This section presents the architecture designed for the SHM system, particularly details the functionality of the main station or gateway and the communication system among the accelerograph stations that was stablished through an Ad hoc network. Additionally, the solution based on the MQTT protocol for detecting seismic events is described. Regarding the scenario under analysis, the architecture was deployed on the headquarter building of The Electricity Company of the city of Cuenca, Ecuador.

2.1 Architecture of the SHM System

The architecture designed for the SHM system is based in a client-server model, where the server consists in a main accelerograph station while the clients correspond to a set of accelerograph stations located in different places along a structure under analysis. In Fig. 1, a general diagram of the proposed architecture is depicted. Particularly, the system allows for deploying a set of stations which can be of two types. The devices named as Sensor Node Station incorporates on the same equipment a Single Board Computer (SBC), specifically a Raspberry Pi, as well as a micro-controlled system which has three main functions: reading samples from an accelerometer sensor, generating a data frame including the sample number and timestamp and finally transmitting data to the SBC platform. The development and evaluation of this instrumentation were previously analyzed in [26].

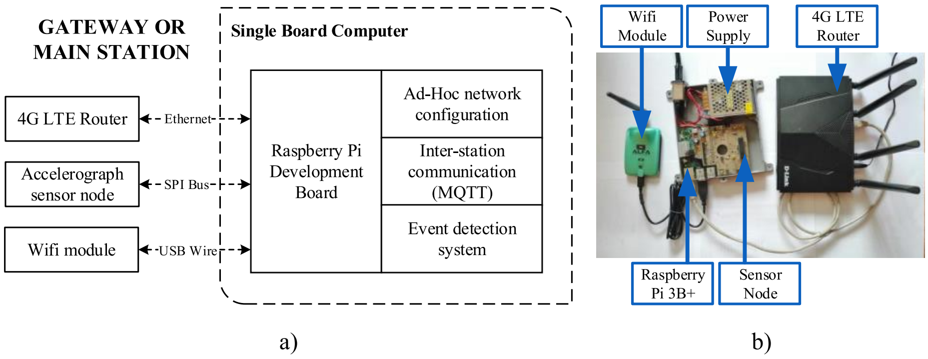

Fig. 2. Main Station. a) Architecture and functionality. b) Implementation and components.

Concerning the stations named as Hub Node, the design presents a variant, in this case, the micro-controlled system and the SBC are separated and the communication was established through the RS-485 standard following and architecture master-slave. This modification allows for transmitting data from more than one sensor (located in different places) to the SBC. Regarding the Main Station, it presents a similar design to the Sensor Node Stations and includes additional capacities as is presented following.

2.2 Main Station

The main station or gateway was implemented on a Raspberry Pi 3B+, its architecture is depicted in the diagram of Fig. 2a. As can be appreciated, the station supports the Ad hoc mode for network communication, this functionality was enabled by means of an external module detailed in [27] that also allows for extending the distance of the link.

With regard to the application layer, the communication is managed by means of the MQTT protocol. It is worth highlighting that the main station not only performs management tasks but also incorporates the capacity of collecting acceleration data through a sensor node attached to the SPI interface of the Raspberry Pi. This last functionality allows for the implementation of a referential system for detecting events.

In addition, with the purpose of providing the system with Internet access, the main station includes an external Router 4G LTE [28] attached to the ethernet interface. Fig. 2b presents a picture of the implementation performed, also the main components are highlighted.

On the other hand, it is important to indicate that the continuous register of information in a sensor node generates a file size of around 200 MB per day. Consequently, in order to reduce the volume of information to be transmitted, it was necessary to design an automatic system for detecting and extracting only the events (i.e., vibrations caused by earthquakes). For this purpose, the Recursive STA/LTA algorithm was implemented using the C programming language, Fig. 3, presents the flow chart for the solution developed.

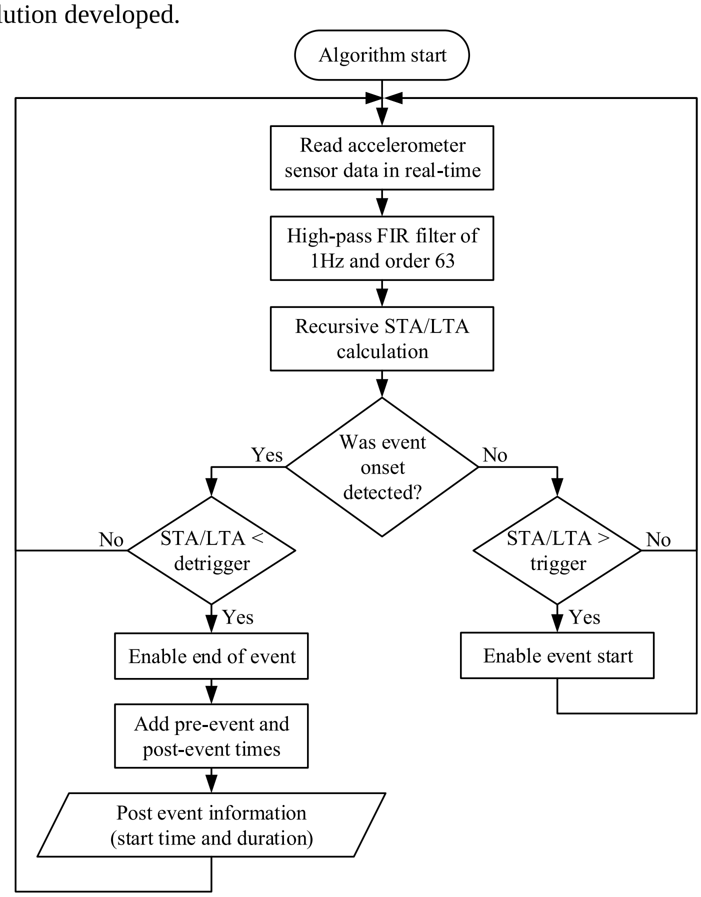

Fig. 3. Flow chart for the automatic event detection system.

The process starts by reading the data from the accelerometer sensor, following an FIR filter (Finite Impulse Response) is applied to the signal in order to eliminate the DC components (Direct Current). Then, the STA/LTA relation is computed and when this value exceeds a trigger threshold (previously defined) the system interprets this behavior as the start of a seismic event. Moreover, the end of an event is defined when the STA/LTA relation is less than the detrigger threshold level. Also, with the purpose of evaluating the seismic noise (i.e., environmental noise) an additional pre- and post-event interval are considered.

It is worth clarifying that the parameters used for processing the signal, i.e., the trigger and detrigger values, the time intervals of pre- and post-event as well as the parameters of the FIR filter, have been determined experimentally following a trial-and-error methodology.

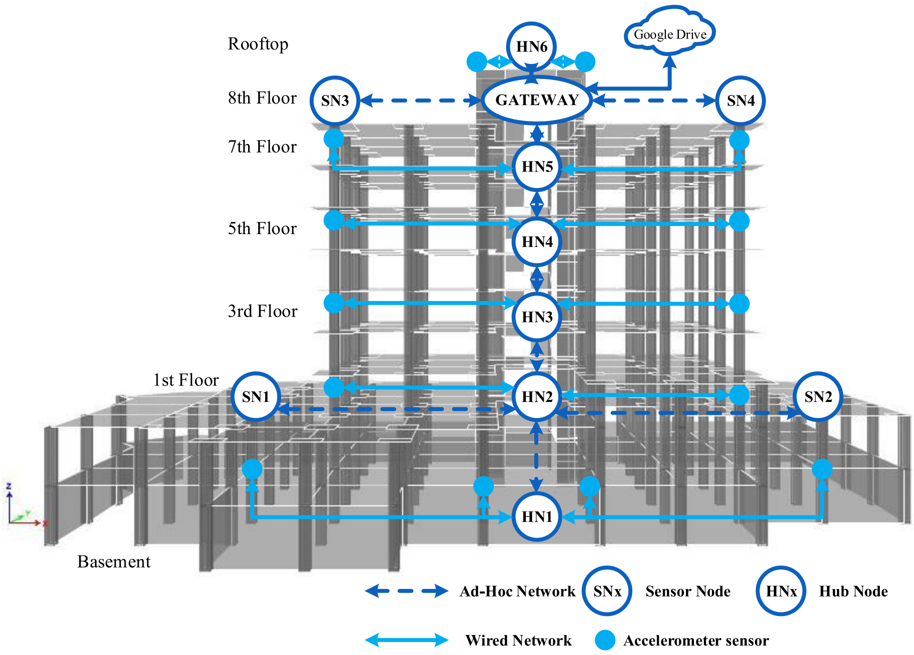

Fig. 4. Network topology designed for the SHM system.

2.3 Communication System

The communication among the main station and the rest of accelerograph stations (i.e., sensor and hub stations) was established through a multi-hop Ad hoc network. The architecture of the system is illustrated in Fig. 4. The location and the number of stations were defined following the methodology described in [4] and [5], from this analysis a set of 18 triaxial accelerometers were distributed along seven floors of the building under study. Specifically, four sensors were placed on the basement, two on opposite columns and two on the concrete walls. On the first floor four additional sensors were installed, in this case, two on indoor columns and two on external concrete slabs. Regarding the floors number 3, 5, 7, it was defined the same sensor configuration consisting in two nodes installed on indoor columns and in the case of the eighth floor two sensors were placed on the concrete slab. Finally, at the rooftop were installed two additional sensors on the core of the concrete walls.

Concerning the main station (gateway) it was placed on the eighth floor as is highlighted on the diagram of Fig. 4. In addition, an application based on the MQTT protocol was developed to manage the exchange of information among the nodes and the gateway. Specifically, it was defined a topic named as EventDetected, as is presented in the functional diagram of Fig. 5.

The application was implemented using the Python programming language, Fig. 6, presents the flow chart of the solution. As can be appreciated, in first place, both the main station and the accelerograph stations are configured. Subsequently, when a seismic event takes place and it is detected by the referential system, the main station publishes the respective notification through the MQTT topic. Following, the accelerograph stations subscribed to the topic receive the message and generate a request for the data captured in each one of its sensors. Finally, the stations upload the files with the information of the events to the Google Drive platform.

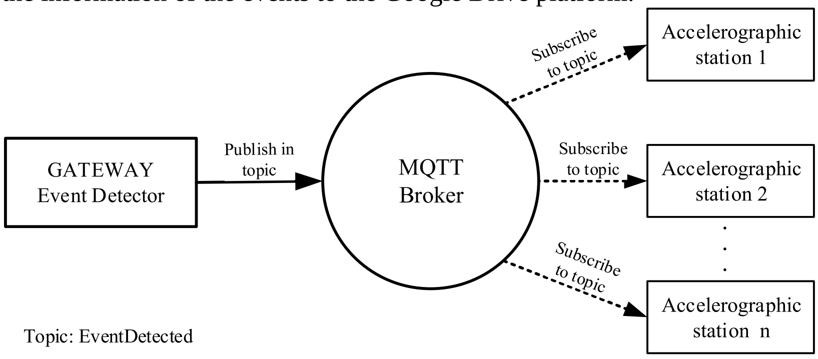

Fig. 5. Schema of the application based on the MQTT protocol for detecting events.

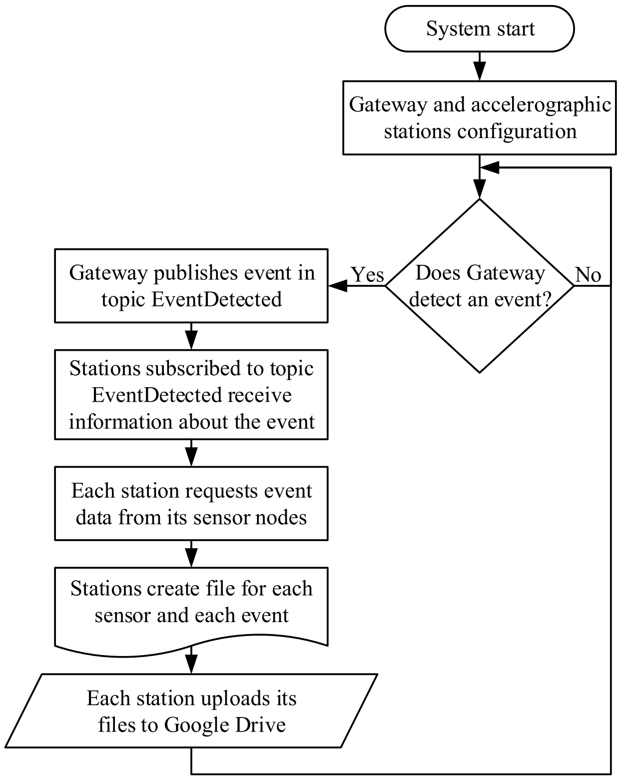

Fig. 6. Flow chart for exchanging information of events between the accelerograph stations.

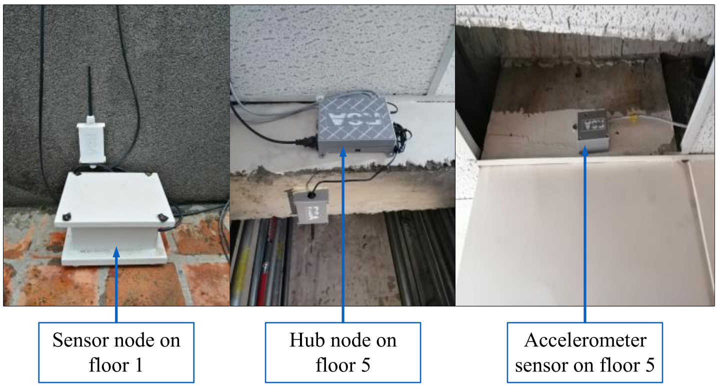

Fig. 7. System set up on the building under analysis.

3 Experimental Evaluation

This section describes the experimental evaluation of the SHM system. Particularly, the set of accelerograph stations were deployed on the headquarter building of The Electricity Company of the city of Cuenca, Ecuador. Fig. 7 presents some pictures of the stations set up on different floors. In addition, results regarding a relevant event detected by the system as well as the respective structural analysis are discussed.

3.1 Seismic Monitoring

The operation of the SHM system was tested over a period of four months, during which a total of ten seismic events were detected by the stations. It is worth indicating that the occurrence of these events was verified against both the reports generated by the USGS Earthquake Hazard Program [29], as well as the reports provided by the regionals networks of seismology [30], [31].

In this context, the event detected on 21 January 2021 deserves special attention due to the magnitude and distance with the site under study (approximately 87 km of the building). The epicenter was located at 2.267° S y 79.458° W (6 km of Coronel Marcelino Maridueña, Ecuador), the event magnitude reported was of 4.9 Md and occurred at a depth of 90.2 km [32]. The accelerograms of the event for the different floors of the building are depicted in Fig. 8. Additionally, the maximum, minimum, and RMS (Root Mean Square) values for the longitudinal, transverse, and vertical axes are detailed in Table 1.

Results show that the acceleration values registered on the basement present the lowest amplitude, whereas the highest values of acceleration were detected on the eighth floor. For instance, regarding the longitudinal axis, the acceleration values on the basement range from -2.35 cm/s^2 to 1.93 cm/s^2 and in the case of the eighth floor range from -10.77 cm/s^2 to 9.28 cm/s^2. Similarly, the RMS values on the basement are 0.26, 0.22, and 0.22 cm/s^2 for the longitudinal, transverse, and vertical axes, respectively. Regarding an intermediate area of the building, for example, on the third floor the RMS values are 0.66, 0.72, and 0.41 cm/s^2 and finally, concerning eighth floor the RMS values are 1.18, 1.33, and 0.59 cm/s^2. Consequently, it can be noted that the acceleration values increase on the upper floors of the building. These results are consistent with the method for computing the acceleration detailed in [33], particularly, the acceleration value increases linearly as a function of the height of a building.

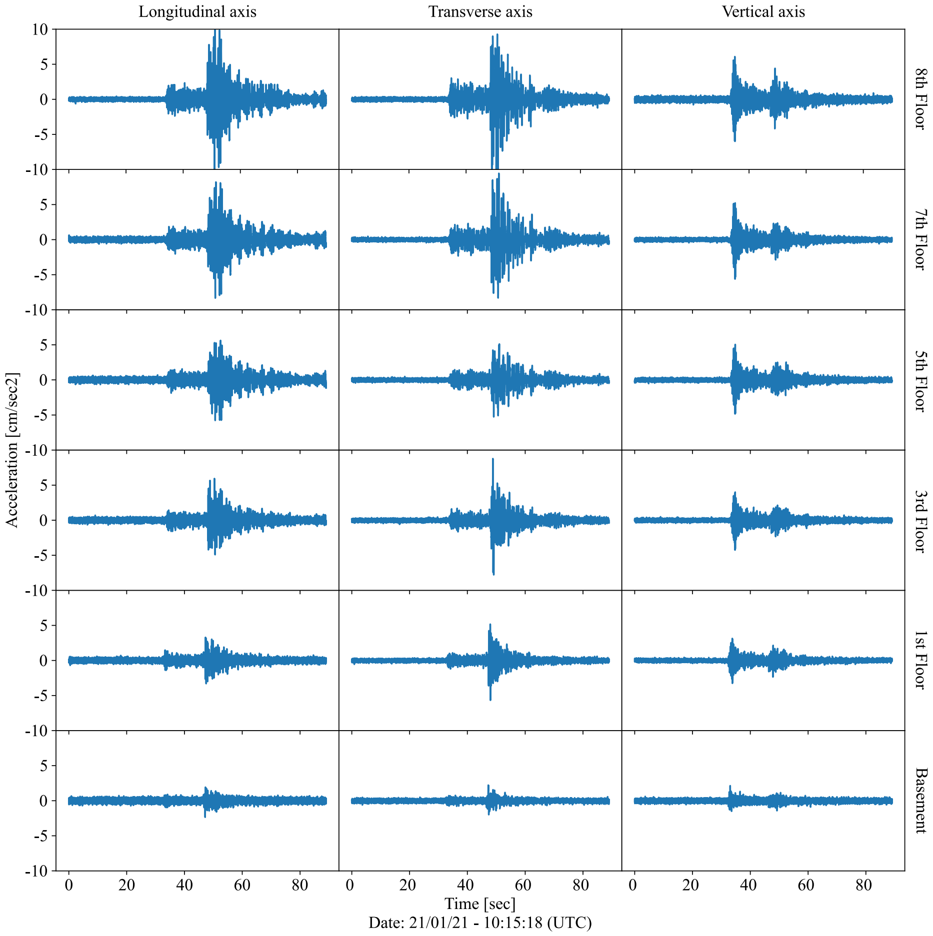

Fig. 8. Accelerograms for the different floors of the building under study.

Furthermore, results show that in all the cases for the different floor of the building the RMS values of the vertical axis are lower than the acceleration values registered for the other two axes, i.e., a seismic event has the greatest effect on the magnitude of the movements along the longitudinal and transverse axes of the building.

Table 1. Acceleration values registered in the building during the seismic event.

Floor	Longitudinal axis			Transverse axis			Vertical axis		
	Max (cm/s²)	Min (cm/s²)	RMS (cm/s²)	Max (cm/s²)	Min (cm/s²)	RMS (cm/s²)	Max (cm/s²)	Min (cm/s²)	RMS (cm/s²)
8	9.28	-10.77	1.18	10.53	-10.52	1.33	6.08	-5.98	0.59
7	8.20	-8.32	1.14	9.44	-8.30	1.04	5.22	-5.61	0.50
5	5.62	-5.78	0.88	5.11	-5.26	0.70	5.04	-4.84	0.48
3	5.92	-4.91	0.66	8.77	-7.78	0.72	3.99	-4.25	0.41
1	3.28	-3.29	0.40	5.16	-5.67	0.49	3.14	-3.25	0.34
Basement	1.93	-2.35	0.26	2.21	-1.98	0.22	2.14	-1.48	0.22

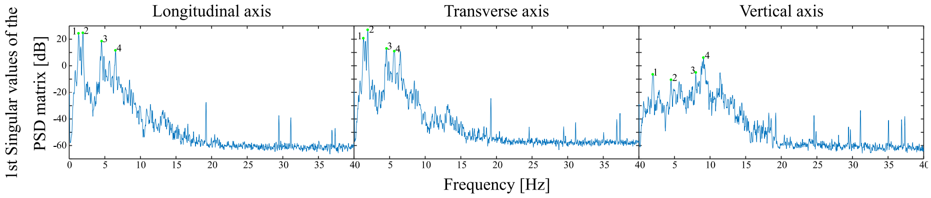

Fig. 9. Peak values selected from the Power Spectral Density Matrix for the longitudinal, transverse, and vertical axis.

Table 2. Values of frequencies identified for each axis using the FDD method.

Axis	Longitudinal				Transverse				Vertical			
Mode	1	2	3	4	1	2	3	4	1	2	3	4
f (Hz)	1.31	1.92	4.55	6.50	1.31	1.92	4.55	5.65	1.93	4.52	7.99	9.06

3.2 Structural Health Assessment

In order to perform an initial assessment regarding the dynamic response of the building, the technique of Operational Modal Analysis was applied, particularly, the Frequency Domain Decomposition (FDD) method which is a mechanism widely used for Structural Health Monitoring as is highlighted in several studies in the literature, for example in [34] and [35].

In this context, the acceleration values of the longitudinal, transverse and vertical axes were analyzed based on the information registered by the sensors during the seismic event occurred on 21 January. Fig. 9 presents the behavior of the Power Spectral Density (PSD), where the first four modes of vibration with the highest values of amplitude were selected for the structural assessment.

Regarding the FDD method, it is worth clarifying that the selection of the peak values is performed by inspection, these values are presented in Table 2. As can be seen, for the longitudinal and transverse axes, the first three frequencies (i.e., 1.31, 1.92, and 4.55 Hz) are the same. These results indicate that such modes of vibrations are not separate modes but composite modes and consequently are present in both axes. Additionally, the vibration modes for the longitudinal axis are depicted in Fig. 10, in this case by means of a simplified model of the building, where it can be appreciated the dynamic behavior of the structure for the four modes obtained. As result of this first assessment, it can be indicated that the composite modes reveal an unsuitable response of the building during a seismic event. Particularly, a seismic-resistant building must be characterized by a dynamic response which not includes composite modes as is detailed in the ACI recommendations [36].

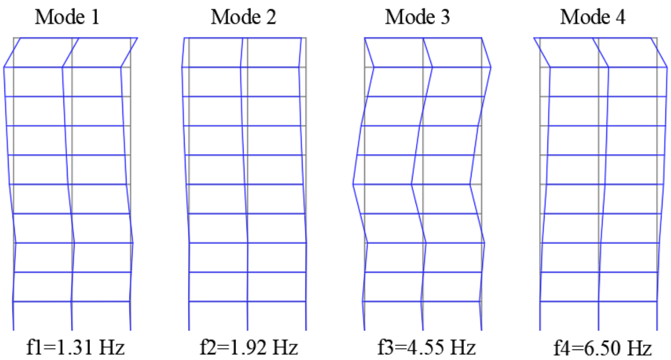

Fig. 10. Vibration modes obtained for the longitudinal axis through the FDD method.

4 Conclusions

In this paper a system for Structural Health Monitoring has been presented, the architecture incorporates an automatic mechanism for detecting seismic events based on the MQTT protocol as well as IoT devices. The main advantages of this solution are scalability, easy adaptation to existing buildings, low bandwidth requirements, and the capacity for monitoring seismic events remotely in real-time.

Regarding the experimental evaluation, it was carried out on an actual building (headquarter building of The Electricity Company of the city of Cuenca, Ecuador), the information captured by the sensors was registered along four months, during which a total of ten seismic events were detected by the stations and the most relevant event was selected for evaluating the dynamic response of the building. Particularly, the maximum, minimum, and RMS values of acceleration were determined for the different floor of the scenario under study. Results show that the magnitude of the acceleration values increases as a function of the building height. Moreover, it was detected that the magnitude of the movements along the longitudinal and transverse axes are higher than the results obtained for the vertical axis.

On the other hand, an initial assessment regarding the structural health status of the building was performed through the OMA methodology. Specifically, the FDD mechanism was used in order to determine the first four frequencies and its respective vibration modes. This first analysis reveals the existence of composite vibration modes where are present in both the longitudinal and the transverse axes which represent a not recommended response of a building during a seismic event. Finally, as future work, evaluations including additional vibration modes will be performed.

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