Sensing the Health State of a City

Structural monitoring system by IoT wireless sensing devices

Paolo Barsocchi*, Pietro Cassará*, Fabio Mavilia* and Daniele Pellegrini*
*Italian National Council of Research, ISTI-CNR, Pisa, Italy

◆

1 INTRODUCTION

We are witnesses of technological ascent accomplished by the Internet of Things (IoT) in the new era of the shared *informatization*. Smart Cities make up certainly one of the major areas of IoT applications. Despite the several definitions for this new concept, the aim is achieve a better use of public resources, increasing the quality of services and decreasing the costs of public services. Some initiatives of Smart Cities around the world have become reality [1]. Many components compose a smart city, e.g. smart transportation, smart energy, smart education, and smart building surely. A smart building consists in services offered to the occupants, resources distributed to the city and, in case of historical heritage, informations about its ”health state” to municipalities. The core of a smart building, and more in general of a smart city, is represented by the IoT devices [2]. Physical objects connected over a network take part in Internet sharing information about themselves at any time. The marketplace offers several solutions for IoT developments, both in hardware and software. Developers have proposed simply and low-cost embedded systems, that allowed users to develop on their own monitoring and actuation systems [3]. The research in the structural health monitoring field (SHM) [4] takes advantage by the IoT paradigm. Indeed, the goal of SHM is to obtain information about the characteristics of a structure, its constituent materials, and the different parts that compose itself. The SHM needs of observations of a structure over the time, using measurements obtained with different kind of sensors (accelerometers, thermometers, hygrometer, extensometers) deployed along the whole structure to be monitored. Such procedures are recognized as a good way to test the state of conservation of a structure, and are also important aids in identifying when interventions are necessary. Exploiting low-invasive and aesthetically acceptable sensors becomes essential to widespread SHM applications. IoT technologies have invaded SHM field providing an economical and relatively non-invasive instruments for real-time structural monitoring of buildings and monuments. Indeed, IoT-based sensors are able to monitor wide areas and transmit data to a remote server. We envisage their employment in a not too distant future in the monitoring of entire areas within a city, facilitating the management of maintenance operations and prompt interventions in the case of an emergency.

The main issues that must be taken into account when an IoT-based sensor network is used for SHM applications are: the number and location of the sensors used to acquire data, the synchronization of the acquired data and the energy consumption of the nodes. The optimization of the number and location of sensors is a new challenge in these technologies, which typically involve a large number of redundant sensors. Moreover, the synchronization of the sampled data is essential in order to correlate data coming from different sensors deployed in the ancient monuments. Finally, adopting energy-efficiency policies becomes essential for long term monitoring systems.

In this paper we show how a long term monitoring infrastructure based on the IoT paradigm can be achieved with off-the-shelf devices, where each sensing device is able of autonomously transferring data (3-axial acceleration, temperature and humidity) to a server. We deployed the sensing devices on the San Frediano bell tower in Lucca, collecting a large amount of data. Finally, we studied the structure behavior under external stresses, showing results in three particular conditions: environmental noise in a weekday, during the ringing of the bells and during a large event taken place in the city.

2 RELATED WORKS

The rapid spread of WS technologies has allowed the replacement of the wired infrastructures with the wireless ones. Wireless infrastructures provide considerable advantages for SHM applications, such as ease deployment of sensor network and high degree of scalability, even in non-urbanized areas [5]. The authors in [6] and [7] describe the development of a dedicated wireless system for the real-time SHM of a historic building. However, the accelerometers resolution cannot be conditioned to evaluate large signal variations that saturate the system output. Another wireless system for SHM of large bridges is presented in [8]. The system exhibits good wireless interface performance in terms of data rate, network scalability and cost, but the resolution is not suitable for ambient vibration acquisition, as it does not provide high enough resolution for such applications. The paper in [9] regards dynamic testing and structural monitoring via wireless sensor networks in the postearthquake assessment of the structural conditions of buildings in L’Aquila. The authors designed an SHM system exploiting commercial wireless transceivers, as well as the Imote2 board for the acquisition of inertial signals.

Transducers are embedded in Imote2 and the hardware configuration, as well as the setup procedure, is impossible to configure in accordance with building requirements. A hybrid system, based on both wired and wireless technologies, is proposed in [10]. Each sensing node collects data from transducers and communicates with its own base station through CAN (wired bus) interface. The system scalability and high cost of dedicated ad-hoc hardware are the significant differences with the proposed system. In [11] authors show the results about the modal analysis performed on two different historical buildings. The proposed system is mainly composed by high-cost transducers, plugged via wire to a commercial acquisition system and directly connected to a laptop for data analysis and storage. Despite the good performance, the system is not suitable for a long term installation, appearing bulky and too invasive. In [12], [13], [14] authors propose some techniques to reduce the energy consumption, i.e. sampling rate adjustment and data compression. The first one is based on reducing the data-sampling rate as much as possible without affecting recognition accuracy [14] . While, the second technique reduces the amount of transmitted data, saving energy that would otherwise be consumed for radio transmission [13]. In this paper, we adopt these two energy saving techniques and we further reduce the energy consumption solving the synchronization issue endowing all WS nodes with a NTP client without waste of energy.

3 HOW TO MONITOR A STRUCTURE

The experimental verification of modal parameters of a structure (eigenfrequencies, damping ratios, modal shapes) is important for its design and it can be used for SHM purposes; indeed the analysis of the variation of these quantities over time, can provide indications relating to a possible structural damage. Therefore the knowledge of the modal parameters is crucial to carry out the structural monitoring. A preliminary experimental campaign performed by a high precision instrumentation can be used to estimate accurately the maximum level of acceleration reached by the structure and to asses its modal parameters. Using vibration data collected is possible to know eigenfrequencies, damping ratios, modal shapes of the structure by numerical techniques known as EMA (Experimental Modal Analysis) or OMA (Operational Modal Analysis) [15]. Once identified the dynamic behavior of the structure, the SHM is possible. The method that underlies to the SHM can be summarized in four phases: system definition, signal processing, data gathering and numerical analysis. Figure 1 shows these phases and how they have been accomplished, jointly to the preliminary experimental campaign to achieve the SHM. The system definition has the aim to establish the type of physical quantity to be monitored and to understand the problems that can arise during the structure monitoring in light of the fact that the preliminary experimental campaign has highlighted. In this phase a fundamental role is given by the choice of the used sensors, and where they will be placed. Through system definition, the target of the monitoring is defined, as well as the features of the monitoring system to analyze the type of physical quantity under observation. The signal process procedure is essential to increase the signal to noise ratio, and it can be achieved through either analogical or digital hardware. Economic considerations and energy efficiency policies play a major role in these two phases. The data gathering involves all the technologies used to collect, transmit and/or storage the data. An important consideration is how often the data should be collected. In some cases, it is adequate to collect data at periodic time intervals, sometimes continuous data acquisition is required. Moreover, how to synchronize the data that are collected from sensors placed in different sections of the structure is crucial to evaluate the global effect of an event on the structure. Finally numerical analysis allows to extract, by using vibration data collected under ambient forces, the dynamic properties of the structure such as natural frequencies, modal shapes and damping of the structure. Known these experimental quantities, a finite element model of the structure can be created via a finite element code and updated to fit the experimental data. Such finite element model will be used to perform further analysis of the structure and to evaluate its safety. In the next section we discuss about the designed system, taking into account the requirements of a monitoring system shown into the table 1a.

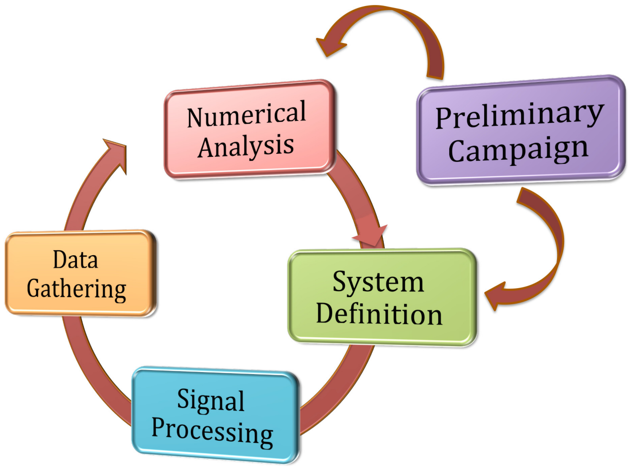


Fig. 1: SHM Phases: system definition, signal processing, data gathering and numerical analysis.

(a) Requirements of the monitoring system

Range Acc. $[m/s^2]$	**Resolution** $[m/s^2]$	**Bandwidth** $[Hz]$
± 20	$\pm 1 - 5 \cdot 10^{-3}$	$25 - 50$

(b) Features of the accelerometers

	Rng. Acc. $[m/s^2]$	**Sens.** $[V/(m/s^2)]$	**AND** $[(m/s^2)/\sqrt{Hz}]$	**Band.** $[Hz]$
LIS 344	± 20 or ± 40	0.066	$5 \cdot 10^{-4}$	1500
M4030	± 20 or ± 60	0.1	$5 \cdot 10^{-4}$	200

TABLE 1

4 SMS: LONG TERM STRUCTURAL MONITORING SYSTEM

After a preliminary experimental campaign which allowed us to know the dynamic behavior of the structure and estimate the maximum level of acceleration caused by ambient

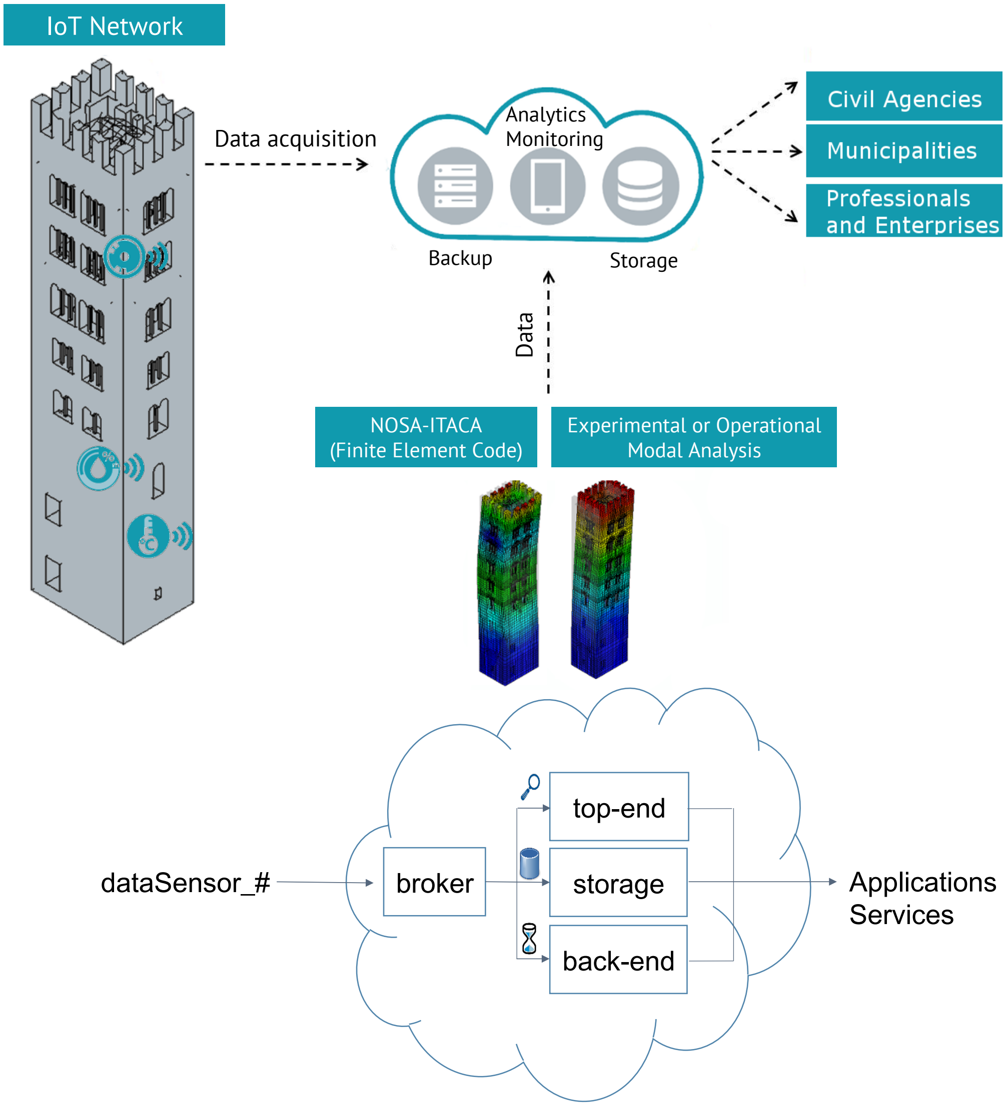


Fig. 2: The architecture and the data workflow.

excitation, we developed a long term monitoring system, hereafter called SMS, taking into account the four aspects previously described.

4.1 System Definition

WS nodes developed for our system have been endowed with low-cost MEMS. Resolution $\mathbf{R}$ represents the strictness constraint of the system (see table 1a). This requirement is strictly correlated with the Acceleration Noise Density (**AND**) and with the bandwidth **B** through the equation $\mathbf{R} = \mathbf{AND}\sqrt{\mathbf{B}}$. **AND** defines the minimum detectable acceleration above and beyond the background noise within the bandwidth of the transduced signal. So, on the basis of equation and the values in table, **AND** must be strictly below $10^{-3}[(m/s^2)/\sqrt{Hz}]$. Among all available commercial accelerometers, the LIS344 [16] and the M4030 [17] have been considered. The features of the both, LIS344 and M4030, are shown into the table 1b. We chose to endow the WS nodes with LIS344 given its best quality-to-price ratio. The sensor nodes are based on the single board computer Galileo by Intel [18]. It is designed to be Arduino hardware compliant and software compatible with Arduino IDE, making it suitable for IoT applications [3]. Accelerometer outputs are connected to an external three-channels 16 bits ADC through I2C interface. We adopted techniques of sampling-rate adjustment to reduce the data sampling rate as much as possible, in order to save energy without affecting the resolution reported in table 1a. Temperature and humidity transducers have also been connected through the analog interface to the board.

4.2 Signal Processing

Due to the low resolution of the used MEMS, we need to perform a signal processing to enhance the signal to noise ratio of the acquired signal. Precisely, we use Finite Impulsive Response (FIR) filters to filter out the Zero-g bias introduced by the MEMS, to limit the bandwidth of the acquired data in the range $0 - 5Hz$ and to decrease the electrostatic noise. In this way, we can get only the signal variations, which carrying the useful information about the natural frequencies of the structure. We, finally, adopted sensor data compression to reduce the amount of transmitted data and to save energy due to data transmission.

4.3 Data Gathering

The architecture of SMS is shown in Figure 2. The acceleration data of all nodes have to be synchronized, otherwise their data become useless for the applications. While in [11] a gateway ensures the nodes synchronization through ad-hoc protocols causing, moreover, a high power consumption, in the proposed system each WS node is independently connected to internet through an IP network. Therefore, the synchronization issue is solved endowing all WS nodes with an NTP client without waste of energy. In order to receive and store data gathered from the WS nodes we configured a back-end messaging service. It is based on a single-core virtual machines provisioned with a MQTT broker (Mosquitto[1]). The chosen communication module leverages a Message-oriented system based on the IoT/M2M MQ Telemetry Transport protocol [19], an extremely lightweight publish/subscribe messaging transport. Moreover, this module, connects directly to the broker with connection failover and message buffering mechanisms, preventing data loss when connectivity issues arise on the IP network. The sensing information received through the messaging service are stored into two different databases. Precisely, part of WS information are stored within a MySQL database, and part in a Mongodb database. MySQL database is used in order to store sensors IDs, type of data acquired and the MAC address of the sensor nodes. These data need to be related among them to provide information also for applications different from the structural monitoring, in the context of the IoT paradigm provided. Instead, the MongoDB non-relational is used to store all the sensing information gathered from the WS nodes. Moreover, the proposed IoT-based infrastructure needs to be supported through top-end services such as monitoring, analytics, backup, REST. The monitoring services implements two operations. Primarily, it offers virtual machine statistics such as peak load, space utilization, hardware resources usage. Moreover, it allows to inspect data stream coming from the IoT nodes. The backup service burns periodically the virtual machines snapshots in order to being able to restore an existing configuration of the services. Finally, the restful API service allows third-party applications (for instance the numerical analysis described in Section 4.4) to retrieve raw and/or aggregated sensing information stored on the databases in order to produce other analysis and statistics.

4.4 Numerical Analysis

As previously mentioned, in OMA the modal proprieties of a structure are extracted from measurement of the vibration response only, assuming that the operational loads (wind, traffic etc) are not disturbance but rather they can replace artificial excitation. In the developed system the EFDD (Enhanced Frequency Domain Decomposition) technique is used; this OMA method allows to estimate the modal parameters by a singular value decomposition of the spectral density matrix of the output data recorded [20]. The finite element model of the structure is made by NOSA-ITACA code [21], a freeware/open-source software for computational mechanics with the aim of disseminating the use of mathematical models and numerical tools in the field of Cultural Heritage. In particular, it can model the mechanical behavior of masonry constructions by the constitutive equation in which masonry is described as a non-linear elastic material with zero tensile strength and finite compressive or bounded resistance.

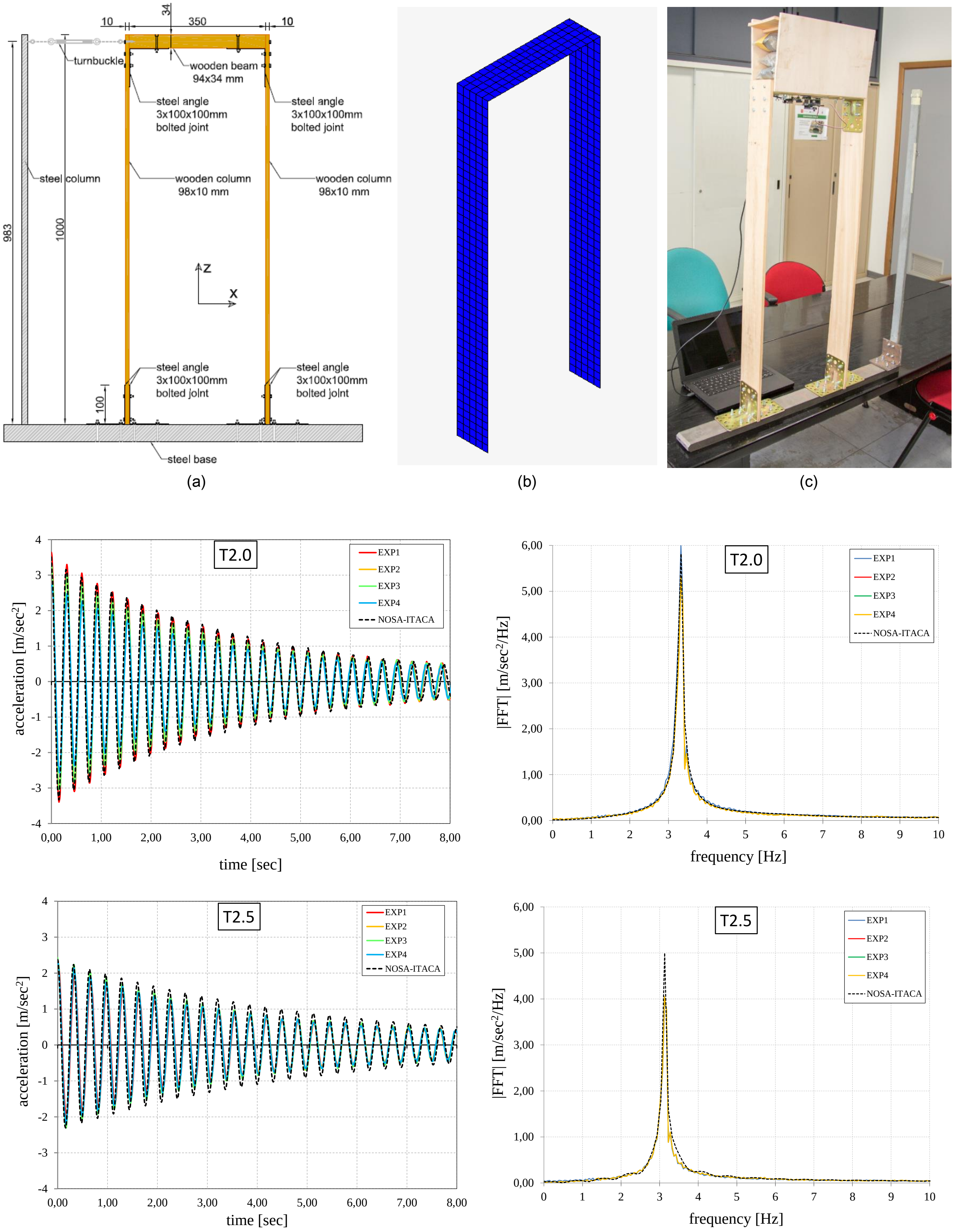
5 SYSTEM VALIDATION

In order to validate the system described in section 4, firstly we verified the proper operation of data acquisition and signal processing, later we verified the system operation performance. For this purpose, we built in laboratory a wooden framed structure. The prototype, shown in figure 3(c) and schematized in figure 3(a), consists of two columns with rectangular cross-section, rigidly connected to an upper rectangular cross-section wooden beam. All connections are ensured through steel angle bracket and bolts, that approximates a perfect joint; this set-up prevents any relative rotation between the wooden structure's elements. The structure is able to oscillate at a given frequency simply by varying the mass of the structure, adding or removing sandbags on the top. As shown in figure 3(b) we built the finite element model of the structure through NOSA-ITACA software (section 4.4). The tests were carried out for different values of the mass and compared with the results of the numerical simulations. We performed eight tests ranging masses from 1 to $4.5\ Kg$. In order to evaluate the stability of the system and the deviation from simulations, we also performed four experiments for each test. The results of two tests $T2.0$ and $T2.5$, at given mass of $2\ Kg$ and $2.5\ Kg$ respectively, are shown in figure 3. In particular, figure 3(d) illustrates the comparison between measured acceleration by the system and the numerical NOSA-ITACA simulations for each experiment. We analyzed the measured accelerations in the frequency domain to calculate the natural mode of the structure. The natural frequencies were obtained as the maximum of the Fourier Transform amplitude. All comparisons show good agreement between the experimental data and the numerical simulations. We observed a measured natural frequency of $3.32\ Hz$ for $T2.0$, that becomes $3.13\ Hz$ for $T2.5$ (figure 3(e)). Peak frequencies, calculated via NOSA-ITACA code, are $3.31\ Hz$ and $3.13\ Hz$ for the same tests, respectively. The relative error amounts to about 0.3% for $T2.0$, while reaches 0% for $T2.5$. Considering the entirety of performed tests, the error committed is below 1.3%. In order to consider the system operation performance, we evaluated the reliability of the SMS system. Reliability has been evaluated as ability of the system to operate without causing malfunctioning.

Structural damage is evaluated by means of a long-term monitoring, comparing the time series collected in several months or even years. A continuous acquisition for SHM applications is unsuitable since leads to a high energy consumption without adding much more information about potential structural damages. In our case, we deployed the IoT nodes on the San Frediano's bell tower (see Section 6.1)

---

[1] http://mosquitto.org



(a) (b) (c)

(d) (e)

Fig. 3: System validation: the wooden framed structure (a) schematized, (b) finite element model and (c) prototype realization. Comparison between NOSA-ITACA simulations and (d) measured acceleration, (e) natural frequencies.

for six months of monitoring, performing 30 minutes per week of data gathering. During the monitoring, there were no system failures and each of six WS nodes has reported correctly the acceleration on the three axes , jointly with the temperature and humidity values, for amount of samples equal to five millions.

6 EXPERIMENTAL CAMPAIGN AND DISCUSSION

The bell tower of San Frediano church in Lucca (Italy), shown in figure 4(b), is a masonry tower $52m$ high built in eleventh century. The thickness of its walls ranges from 2.1 m to 1.6 m, from the base to the top, respectively. Inside the tower there are not structural elements, apart from the staircase that runs along the perimeter for $38m$ high. The staircase allows to access at the bell floor, indicated with Sec. 2 in the figure 4(a), from which it is possible to reach a wooden floor (Sec. 1) that supports the bell infrastructure. In June 2015, a preliminary experimental campaign was carried out by a sophisticated and high precision instrumentation, usually employed in seismic monitoring networks, made available by the Osservatorio Sismologico of Arezzo. The recorded data processing by an OMA technique allowed us to collect a lot information about modal properties of the tower reported in table 4(c). A finite-element model of the structure has been built via the NOSA-ITACA code and updated to fit the experimental data, allowing the estimation of the mechanical properties of the materials of the structure [22], [23].

6.1 Evaluate the Structural Behaviour Of The Bell Tower

The SMS has been installed on the San Frediano's bell tower, placing the IoT sensor nodes, as depicted in Figure 4 (a), in two different section of the tower. We chose to install the sensor devices on the top of the tower since the measured displacement is maximum. Through the proposed monitoring infrastructure, we are able to monitor the induced effect on the tower produced by movements of the bells as well as the vibrations induced such as crowd, traffic and wind. The acceleration power spectrum has been evaluated by the analysis of the data along the main directions of the tower indicated with X and Y in Figure 4(a). The main natural frequencies of the tower fall into the range $0 - 5\ Hz$, as obtained and described in [22].

Figures 5b and 5a show the power spectrum of the acceleration data from nodes of section 1 in two different events. Precisely, Figure 5b shows the power spectrum during the ringing of the bells in a day of the week, while Figure 5a shows the power spectrum when the tower is subject only to environmental noise. The power peaks, due to the bell oscillations, are close to the first and second natural frequency of the tower, as shown in Figure 5b. However, in this case, in order to estimate the exact eigenfrequencies of the structure, is necessary not only to record the tower vibration but also the bell acceleration and apply an EMA technique. Instead, the environmental noise is able to excite the natural frequencies with lowest intensity; for this reason, the transducer is not able to detected the power peaks, as shown in Figure 5a.

6.2 Beyond the structural Monitoring: Capturing the Rhythm of the city

Lucca Comics Festival is the largest book and games convention in Europe and the second biggest in the world, able to attract in October 2015, inside the ancient walls of the old city, four hundred thousand people. Analyzing the collected data during the Festival, we observed that the crowd next to the tower was able to excite the main natural modes of the tower. Indeed, as shown in the following, the natural frequencies of the tower gain energy thanks to the solicitations induced by the crowd on the tower base. Moreover, we observed that the solicitations due to the crowd excite the natural frequencies of the tower, in a different way by the oscillation of the bell. Also in this case we compare the power spectrum of the acceleration induced by the crowd on the tower, with those ones induced by the environmental noise in a weekday. Figure 5c shows the power intensity of the modes of the tower during the Lucca Comics Festival, while Figure 5a shows the power intensity of the modes for the same window of time but for a week day. The difference of power of the frequencies is notable for the two different days taken into account. Figure 5c shows that for the whole observation window, the natural frequencies of the tower are excited through a higher energy than in the case of the week day.

Another interesting comparison is between the power spectrum of Figure 5c with that one in Figure 5b. The comparison reveals that the excitation of the frequencies due to the crowd is of higher intensity than that one due to the oscillations of the bells. Even if the results shown in this section are preliminary, from this analysis it emerges that the presence of a large amount of people has an impact. Hence, new scenarios for the monitoring of cities can be investigated, for applications such as prevention of potential hazards. In a futuristic scenario, if the SMS will be deployed on many monuments of a city, and algorithms able to extract more detailed informations about the crowd (e.g., size and distance from the monitored structure) will be provided, the crowd movements can be understood in real time. Hence, the evacuation routes or the collection points could be dynamically chosen by the municipalities that manage the events.

7 ACKNOWLEDGEMENT

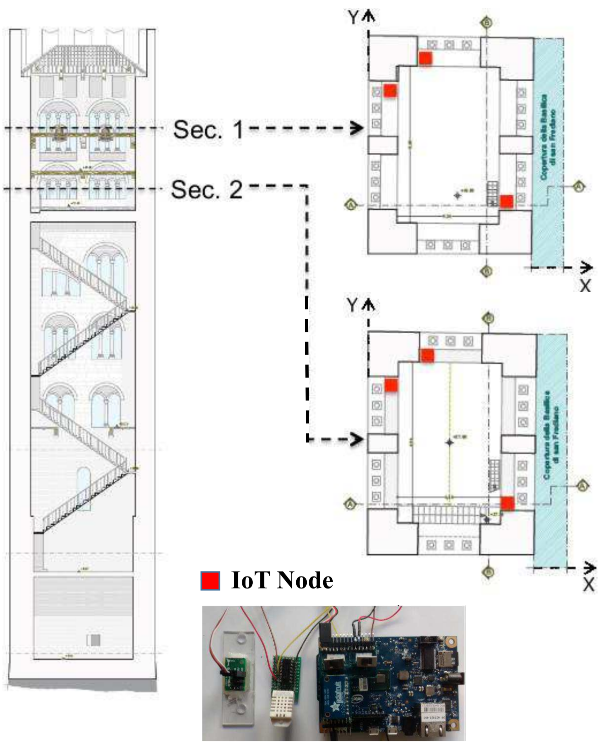
This research was partially supported by project MOSCARDO in the funding framework FAR/FAS 2014-2016 of the Regione Toscana.

REFERENCES

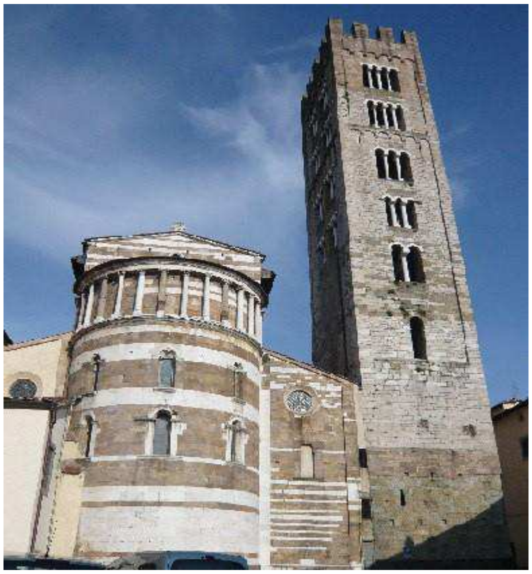
[1] L. Sanchez, L. Muñoz, J. A. Galache, P. Sotres, J. R. Santana, V. Gutierrez, R. Ramdhany, A. Gluhak, S. Krco, E. Theodoridis, et al., "Smartsantander: Iot experimentation over a smart city testbed," Computer Networks, vol. 61, pp. 217–238, 2014.

[2] S. P. Mohanty, U. Choppali, and E. Kougianos, "Everything you wanted to know about smart cities: The internet of things is the backbone," IEEE Consumer Electronics Magazine, vol. 5, no. 3, pp. 60–70, 2016.

[3] K. J. Singh and D. S. Kapoor, "Create your own internet of things: A survey of iot platforms." IEEE Consumer Electronics Magazine, vol. 6, no. 2, pp. 57–68, 2017.



(a)



(b)

	Frequency [Hz]	Damping [%]
Mode 1	1.10	1.05
Mode 2	1.38	1.02
Mode 3	3.44	0.76

(c)

Fig. 4: (a) Deploy of the IoT devices into the bell tower and a miniaturized picture of IoT node; (b) external picture of the San Frediano bell tower; (c) modal properties of the bell tower.

[4] C. R. Farrar and K. Worden, "An introduction to structural health monitoring," Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, vol. 365, no. 1851, pp. 303–315, 2007.

[5] M. L. Rajaram, E. Kougianos, S. P. Mohanty, and U. Choppali, "Wireless sensor network simulation frameworks: A tutorial review: Matlab/simulink bests the rest," IEEE Consumer Electronics Magazine, vol. 5, no. 2, pp. 63–69, 2016.

[6] D. Zonta, M. Pozzi, and P. Zanon, "Managing the historical heritage using distributed technologies," International Journal of Architectural Heritage, vol. 2, no. (3), pp. 200–225, 2008.

[7] D. Zonta and et all., "Wireless sensor networks for permanent health monitoring of historic buildings," Smart Structures and Systems, vol. 6, no. (5-6), pp. 595–618, 2010.

[8] Z. Liu and et all., "Design of a wireless measurement system based on wsns for large bridges," Elsevier Measurement, vol. 50, pp. 324–330, 2014.

[9] E. Antonacci and et all., "Dynamic testing and health monitoring via wireless sensor networks in the postearthquake assessment of structural condition at l'aquila," in Proceeding of Int. Conf. on Structural Dynamics (EURODYN), July 2011.

[10] C. Alippi, R. Camplani, A. Marullo, and M. Roveri, A high-frequency sampling monitoring system for environmental and structural applications, vol. 9, no. 4, 2013.

[11] L. M. L.F. Ramos, P. Lourenço, G. D. Roeck, A. Campos-Costa, and J. Roque, "Monitoring historical masonry structures with operational modal analysis: Two case studies," Mechanical Systems and Signal Processing, vol. 24, no. 5, 2010.

[12] J. P. Lynch, A. Sundararajan, K. H. Law, A. S. Kiremidjian, and E. Carryer, "Embedding damage detection algorithms in a wireless sensing unit for operational power efficiency," Smart Materials and Structures, vol. 13, no. 4, pp. 800–810, 2004.

[13] Y. Lee, S. Iyengar, C. Min, Y. Ju, S. Kang, T. Park, J. Lee, Y. Rhee, and J. Song, "Mobicon: a mobile context-monitoring platform," Communications of the ACM, vol. 55, no. 3, pp. 54–65, 2012.

[14] N. B. Bharatula, M. Stäger, P. Lukowicz, and G. Tröster, "Empirical study of design choices in multi-sensor context recognition systems," in IFAWC-International Forum on Applied Wearable Computing. VDE VERLAG GmbH, 2005.

[15] E. Reynders, "System identification methods for (operational) modal analysis: review and comparison," Archives of Computational Methods in Engineering, vol. 19, no. 1, pp. 51–124, 2012.

[16] STMicroelectronics. (2015) Lis 344 datasheet. [Online]. Available: http://www.st.com/content/st_com/en/products/mems-and-sensors/accelerometers/lis344alh.html

[17] Measurement and Specialties. (2015) M4030 datasheet. [Online]. Available: www.meas-spec.com/downloads/4030-Accelerometer.pdf

[18] Intel. Galileo board. [Online]. Available: http://www.intel.it/content/www/it/it/do-it-yourself/galileo-maker-quark-board.html

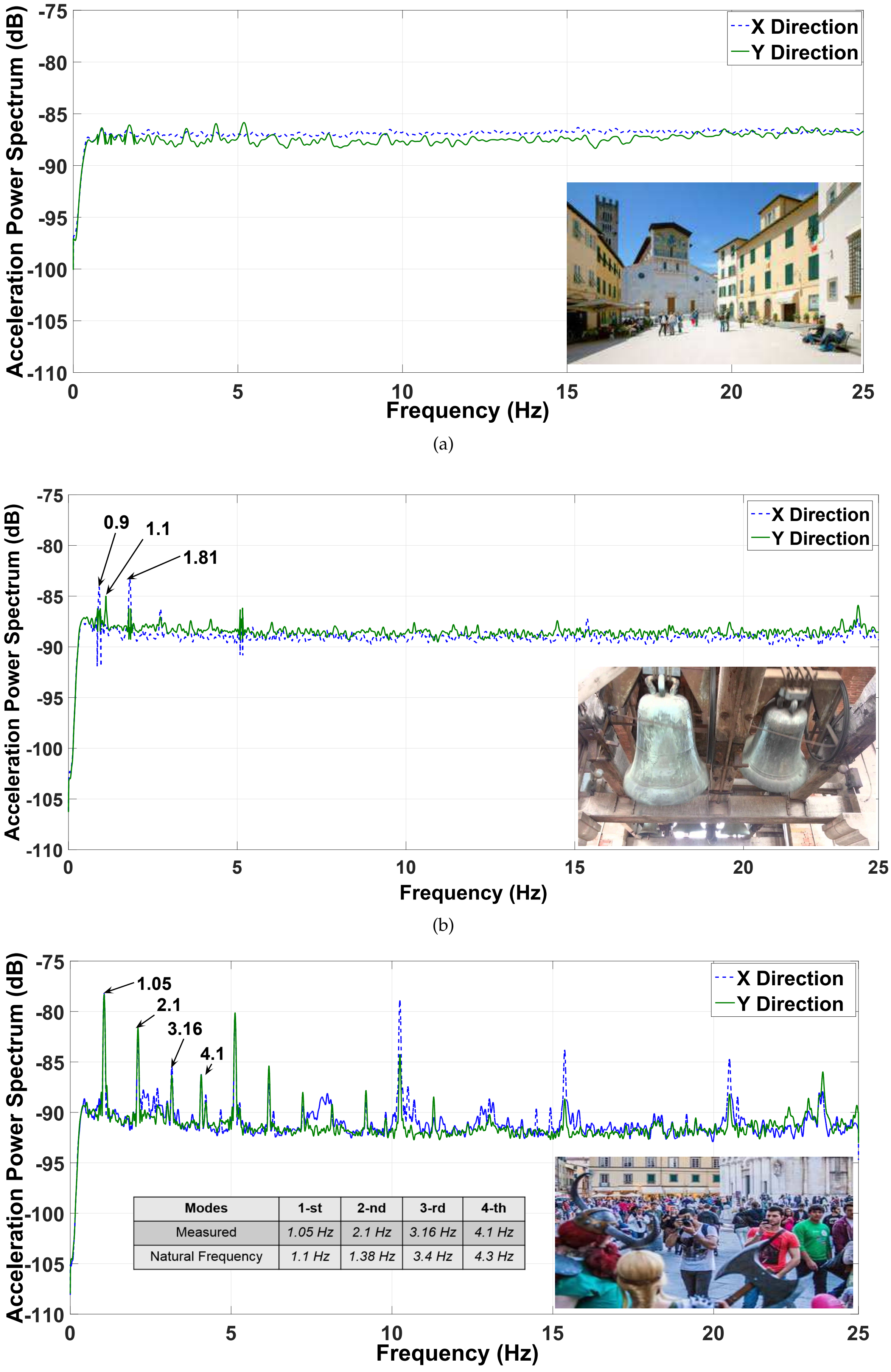
[19] M. ORG. (2014) Mqtt protocol. [Online]. Available: mqtt.org

[20] M. Batel, "Operational modal analysis-another way of doing modal testing," Sound and Vibration, vol. 36, no. 8, pp. 22–27, 2002.

[21] Binante, Vincenzo and Girardi, Maria and Padovani, Cristina and Pasquinelli, Giuseppe and Pellegrini, Daniele and Porcelli, Margherita, "Nosa-itaca 1.0," 2014. [Online]. Available: http://www.nosaitaca.it/en/

[22] R. M. Azzara, G. De Roeck, M. Girardi, C. Padovani, D. Pellegrini, and E. Reynders, "Assessment of the dynamic behaviour of an ancient masonry tower in lucca via ambient vibrations," in Proceeding of 10th International Conference on Structural Analysis of Historical Constructions SAHC 2016 - Anamnesis, Diagnosis, Therapy. in publishing, Sep 2016.

[23] P. Barsocchi, P. Cassarà, E. Ferro, M. Girardi, F. Mavilia, C. Padovani, and D. Pellegrini, "A new tool for monitoring and assessing the structural health of ancient masonry construction," in Fifteenth International Conference on Civil, Structural and Environmental Engineering Computing, ser. BuildSys'13. Civil-Comp Press, 2015, pp. 9:1–9:8.



(a)

(b)

Modes	1-st	2-nd	3-rd	4-th
Measured	*1.05 Hz*	*2.1 Hz*	*3.16 Hz*	*4.1 Hz*
Natural Frequency	*1.1 Hz*	*1.38 Hz*	*3.4 Hz*	*4.3 Hz*

(c)

Fig. 5: Acceleration power spectrum analysis.