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Wireless and Low-Power System for Synchronous and Real-Time Structural-Damage Assessment

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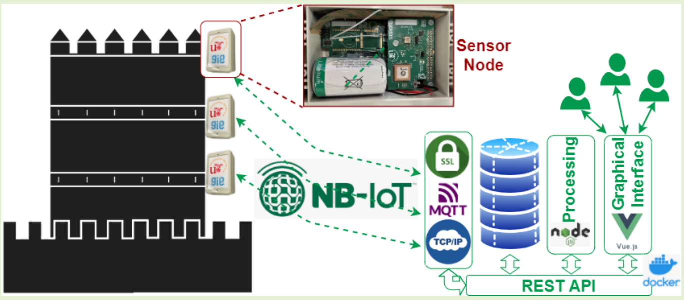
***Abstract*— The rise of Internet of Things (IoT) systems and the evolution of Low-Power Wide-Area Networks have directly contributed to the emergence of a new generation of Structural Health Monitoring (SHM) systems based on the Non-Destructive Test approach. Consequently, this article presents the design and development of a synchronous, low-cost, real-time, wireless, and low-power consumption SHM system for pre-existing buildings and infrastructures, which has been validated on a structure built in the High Middle Ages forming part of the historical heritage of the city of Seville (Spain). The system proposes a modular and scalable design with the capacity for synchronous monitoring of the accelerations of a structure thanks to the deployment of several reduced-size nodes that acquire and transmit the accelerations of the structures through a Secure Sockets Layer (SSL) NB-IoT connection. This aspect and Firmware Over The Air (FOTA) capability enables the permanent deployment of sensor nodes, thereby not only obviating the use of costly traditional devices but also granting access to the structures to be monitored for each test and maintenance task and hence supporting the tasks related to the preventive conservation of heritage. The experimental tests carried out demonstrate the low impact of GPS time synchronization and FOTA on the autonomy of the system. The precision of the system is also validated by comparing the results with a precision system in a real field test. Furthermore, continuous monitoring is guaranteed through the graphical interface developed as a composition of microservices, which enables management of the deployed networks.**



***Index Terms*— Internet of Things (IoT), Low-Cost SHM Nodes, NB-IoT, SHM, Synchronous Structural Health Monitoring, Wireless Sensor Networks, Non-Destructive Test (NDT), Built Heritage.**

I. Introduction

TODAY´S society is highly dependent on the mechanical and structural systems on which it is based, such as viaducts, bridges, dams, and buildings, which suffer from ageing due to the passage of time and exposure to unforeseen working conditions. Generally, for economic or functional reasons, these structures cannot be replaced and hence it is necessary to monitor them so that their working condition is known by the entity in charge of operating the structure. In this way, the detection of damage, its quantification, and even a constantly-updated forecast of the useful life of the structure can be achieved, so that the useful life of the structure can be maximised.

Structural Health Monitoring (SHM) is defined as [1] “the process of implementing a damage-detection strategy in an aerospace, civil, or mechanical infrastructure”, which includes the observation of the structure through its dynamic response, the acquisition of data relating to the occurrence of possible damage, and the statistical analysis of these characteristics to determine the current state of conservation of the structure.

Traditionally, due to the high cost of the test devices (in excess of 15,000 €) the evaluation of the structural health of key structures of society has been carried out either in a discrete manner after a seismic event or accident thereon, or periodically after long periods of time. Cost prohibits its permanent installation and implies the repeated need for specially qualified staff to carry out installations and measurements in locations that are often difficult to access.

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All this supposes an added difficulty for the evaluation of the structural health of such constructions, which would aid in the prevention of events that may have a socio-economic impact on their geographical area of influence (e.g., bridge collapse, road closures, and dam closures) [2][3]. This can be extrapolated to the structures that make up the historical heritage of cities, which are fundamental elements for their identity thanks to their visual impact and historical value.

For all the above, the evaluation of the structural health of historical heritage has become a fundamental aspect in the maximisation of its lifetime by using devices that cause no visual pollution nor render the structures unusable during the process of evaluating their health. This implies unattended, small, inobtrusive devices of low power consumption.

Lastly, the quality of the damage assessment on the monitored heritage structures depends on the quality of the measurements carried out, which has a direct impact on the devices and the measurement procedure. This means that the use of accurate accelerometers and the taking and transmission of time series must be in sufficient detail to enable the application of structural analysis techniques. Furthermore, the structural analysis techniques implies the temporal synchronization of the measurement devices, which is a challenge, especially in wireless networks of low consumption [4].

Through this work, the design and validation of a synchronous, permanent, low-cost, highly optimized power-consumption, wireless, unattended, SHM system of a large time-series is presented, offering a whole solution to the aforementioned problem. Thus, the administration can ascertain an updated characterization of the health of the assets they manage without the need for intervention thereon.

Section II details the work related to this research and its main contributions. Moreover, Section III (System Overview) shows a general presentation of the developed system, by considering the main functional elements, which are detailed in Section IV (Implementation Details). The system characterisation, the parameterisation of the node's functionalities, and the applied test developed on a significant historical heritage building of the city of Seville (Spain), in the form of the White Tower of the Macarena Wall, are illustrated in Section V (Experimental Results). Finally, Section VI (Conclusions) highlights the benefits of the developed system in comparison with other commercial systemsform of the White Tower of the Macarena Wall, are illustrated in Section V (Experimental Results). Finally, Section VI (Conclusions) highlights the benefits of the developed system in comparison with other commercial systems.

II. RELATED WORKS

A. Traditional solutions

Nowadays, various strategies can be considered in order to achieve a structural diagnosis of a specific construction. These include visual inspections, taking samples of materials from the building, and the use of Non-Destructive Tests (NDTs) [5]. Among this latter group of inspection techniques, the use of vibration-based inspection is popular among architects and engineers. By measuring the accelerations experienced by the structure, it is possible to identify changes in its dynamic properties and, ultimately, the presence of structural damage.

Regarding the measurement of ambient vibrations, data collection is carried out by means of several commercial accelerographs installed on the structure. Several of these instruments include a built-in GPS, which enables data to be selected related to the same time period. Moreover, these devices are usually equipped with a 24-bit Analog-to-Digital Converter (ADC), which is over and above the 16 bits required for the dynamic characterisation of structures [6]-[8]. Consequently, very accurate acceleration measurements are obtained. However, these accelerographs are expensive, thereby rendering it unfeasible to work with many devices simultaneously or to leave them on the structure for long periods of time. Furthermore, certain models are cumbersome, which makes them difficult to transport and place on the structure.

B. Research solutions

In the recent literature, a variety of solutions has been presented for the wireless SHM of civil structures whose main innovations and contributions have been largely focused on the optimisation of architecture and known functionalities or on the damage identification technique applied, as stated in [9]. In this respect, [10] presents a wired SHM system based on the Edge Computing application on the data acquired by the accelerometers deployed on this structure monitored using a Raspberry Pi 4 device self-powered with a solar panel and an NarrowBand Internet of Things (NB-IoT) transceiver. Along the same lines, [11] performs laboratory validation of a monitoring system based on accelerations, by sending data through NB-IoT(User Datagram Protocol - UDP). At this point, due to the complexity of combining low consumption with the wireless sending of large time series, new research into the minimisation of the amount of data to be sent wirelessly becomes highly relevant, such as in [12], where the use of compressive sensing techniques is proposed, and in [13], where the eS-TSQR algorithm is applied on an M33 microcontroller.

On the other hand, as far as identification techniques are concerned, there are various comparisons of the different machine-learning algorithms and their application, such as in [14], where a compilation is presented of several machine-learning algorithms for damage detection applied to both vibration and vision-based systems, and in [15], where a built element is monitored by a group of sensors of different nature (e.g., strain, displacement, temperature, and vibration).

C. New features of the proposed solution

The main objective of this work involves the design and development not only of a complete cyber-physical system capable of smart, precise, wireless, and synchronous structural monitoring that enables its massive deployment, but also its scalability and remote exploitation.

As shown in previous paragraphs, there are multiple solutions for structural health monitoring that include traditional methods as well as the most innovative solutions that are developed within the framework of the Internet of Things (IoT) paradigm. Nevertheless, the bar has been set very high regarding the requirements to be satisfied in order, on the one hand, to offer measurement and processing of sufficiently high quality for the application of structural analysis and, on the other hand, to comply with the guidelines for IoT devices. This causes existing developments to opt for compromised solutions that fail to meet all the aforementioned requirements. This work integrates a series of contributions towards existing solutions so that the desired functional requirements can be met:

Holistic and versatile solution: This work presents a complete solution (measurement devices, processing server, and exploitation/management interface) that enables both monitoring and distributed data processing by applying Edge Computing algorithms in the deployed nodes since it uses a FreeRTOS task architecture, which can be simply scaled up. It also enables the application of traditional techniques and machine-learning algorithms [3-2] at the central server over the data lake of information sent by the measurement nodes, thereby aligning this work with the current trend as far as structural health monitoring and machine-learning techniques are concerned, by enabling their integration and taking advantage of the synergies between both fields of application.

Time synchronisation: Thanks to the incorporation of a Global Positioning Signal (GPS) device in the nodes, the time synchronisation of the data series recorded by each measurement node is guaranteed, which permits the application of both traditional structural analysis techniques, such as Operational Modal Analysis (OMA), and innovative machine-learning algorithms.

Secure IoT connections (SSL+Message Queuing Telemetry Transport -MQTT-+Trannsmission Control Protocol -TCP-): This guarantees, on the one hand, the delivery and integrity of the information collected in the monitored structures, which may be of a strategic nature (e.g., heritage, bridges, and dams) and, on the other hand, the inclusion of monitoring devices into the IoT paradigm, which is crucial for their direct integration into commercial and/or standardised information systems (e.g., algorithms, information maintenance, and generation of data lakes). The low energy consumption achieved in the designed nodes allows the application of this communication stack, which has a direct impact on this characteristic, without put at risk the desired autonomy, making this work a novelty solution from the existing ones in this state-of-the-art field.

Scalable system: The integration of new sensory variables without the need to modify the magnitudes already integrated is made possible due to the development of a modular hardware and firmware architecture (detailed in Section IV) and a self-contained data model.

FOTA (Firmware Over The Air): This is an enabling feature for the possible massive deployment of the solution in the field, since it is a wireless and remote firmware update of the devices, which permits the deployment of an in-person unattended solution. It is therefore, possible to modify any functionality controlled by the node´s firmware, such as the acquisition of the sensors, the behaviour of the node (e.g., frequency and measurement resolution, periodicity), and the configuration of the wireless transceiver. On the other hand, FOTA would permit the deployment and remote management of machine-learning algorithms which, due to their current rapid evolution, must be regularly retrained and updated by new versions. Therefore, FOTA guarantees the maintenance and updating of the deployed devices as well as the incorporation of these new functionalities that are desired or that may appear due to the evolution of the state of the art (e.g., security, precision, and stability). Although it is a fundamental feature, which is widely known by the community, it needs to be deployed on a secure and low-power system architecture like the one presented in this work, which has a sufficient degree of maturity that makes it the only solution in this field of the state of the art that presents this characteristic and that, therefore, distinguishes it from the rest.

III. SYSTEM OVERVIEW

As previously mentioned, this article presents a low-cost, wireless, unattended SHM System with a highly optimised power consumption, that offers a complete solution for structural health assessment of monitored assets. This solution is implemented in accordance with Fig. 1, which is made up of four fundamental elements, as detailed in the next section:

- Monitoring nodes, which are deployed in the structure to be monitored and are responsible for acquiring the structural characteristics. These are synchronous, small-sized, low-cost, and functionally upgradable remote devices that can be permanently installed in structures for periodic monitoring.
- NB-IoT communications network that provides the monitoring nodes with sufficiently good connectivity to transmit the information acquired.
- Private cloud and server that, since it possesses a private database, takes the data from the monitoring nodes, processes it, and offers its results to the users.
- A Human-Machine Interface (HMI) served through a secure interface that offers the information from the private server to the users through an intuitive Graphical User Interface (GUI), so that the users are made aware of the status of the various assets in an effortless way.

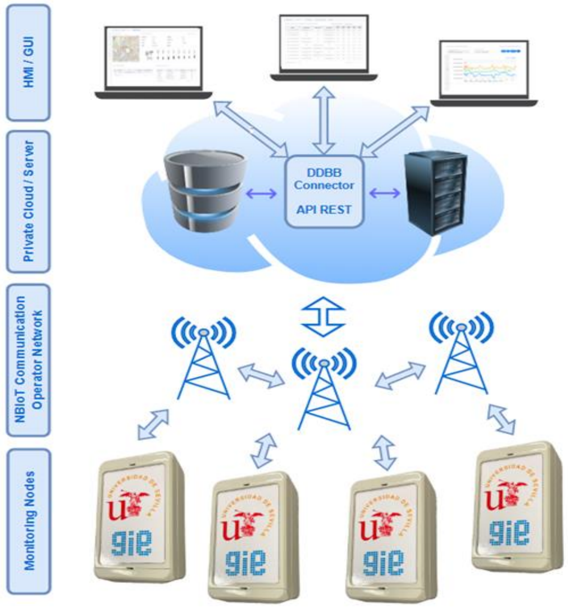


Fig. 1. System Overview

As mentioned above, the following section details the implementation aspects of each of the elements that comprise the system: monitoring nodes, NB-IoT communication network, and the private server, and its graphical interface.

IV. IMPLEMENTATION DETAILS

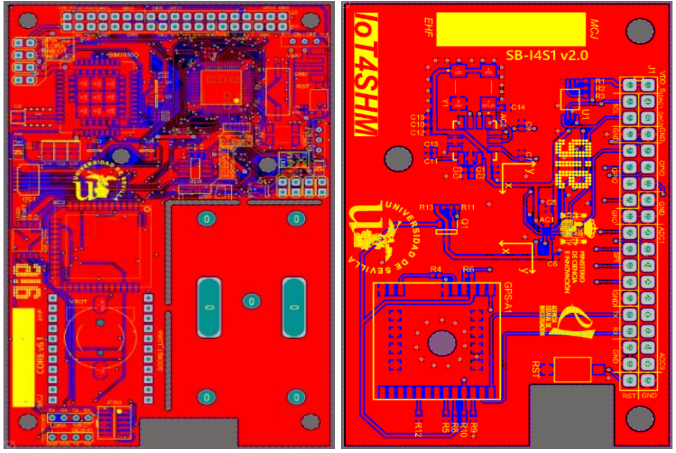
A. Monitoring Nodes

The development of the monitoring nodes is divided, on the one hand, into the design of the hardware and the composition of all the elements that make up the node and, on the other hand, into the design of the firmware that implements the functionality of the devices.

1) *Hardware design*

The hardware development has been carried out as a modular design to facilitate the scalability of the capacities of the nodes, and to allow its portability and its expansion to other IoT applications. For this reason, the functionality of the nodes has been divided into two interconnected boards inside the same enclosure: the Core Board (Fig. 2a), which has processing capacity and is responsible for controlling the interfaces of the microprocessor, memory, power supply, and wireless communications; and the Sensor Board (Fig. 2b), which has the ability to sense and communicate with the Core Board.

The Core Board, which is responsible for the management and processing of information, has a low-cost and low-power microprocessor, such as the ARM Cortex M3 STM32L152RET from the manufacturer ST, which offers both sufficient processing capacity for the desired application and a very low consumption rate (214µA/MHz). The setup operates with a 4MHz High-Speed External (HSE) clock and a 32.768KHz Low-Speed External (LSE) clock. In addition to the 80KB of SRAM and the 16KB of EEPROM of the microprocessor, the Core Board has a 24LC1025 memory of 1Mbit storage capacity and an interface for micro-SD cards where the measurements acquired are stored in case of an occasional lack of wireless coverage. These samples are then sent in the following cycle of operation, thereby guaranteeing the traceability of the information acquired from a temporal point of view. Finally, the Core has a multiband NB-IoT transceiver model SIM7080G that offers a consumption of 3.2uA in PSM (Power Save Mode) mode.



a) *b)*

Fig. 2. Hardware design: a) Core Board. b) Sensor Board

The Sensor Board, which oversees the fundamental characteristics of the structure, has two fundamental elements, such as the ADXL355 3-Axis MEMS Accelerometer and the A2235H GPS module:

- The ADXL355 is a 20-bit (3.81ng/LSB), low-noise(22.5µg/√Hz) digital accelerometer (SPI and I2C) of low current consumption (21µA in Standby mode). This device is referenced for SHM, IoT, and seismic monitoring applications by its manufacturer. In the application presented, the clock signal that controls the Output Data Rate of the accelerometer (ODR) is generated from the microprocessor to improve the accuracy with respect to the use of the internal clock of the accelerometer.
- The GPS A2235H is an integrated module with a patch-type antenna and high sensitivity (-163dBm). As addressed previously, the functionality of this element is fundamental since it is the module that permits the time synchronisation between the different monitoring nodes. While other authors use the wireless communication technology for this purpose [16], we opt for a specific synchronisation technology, thereby making it and communication technologies functionally independent and achieving a more versatile device. The implementation details are laid out below.

Lastly, the node is assembled (Fig. 3) in a Bocube B 140804 ABS 7035 model enclosure (IP68 protection). A Printed Circuit Board (PCB) antenna model W3554B0140T with a gain of up to 3.2 dBi is installed inside the node thereby avoiding external elements and the LSP 33600-20F model battery, which has a capacity of 17Ah, and a 20F supercapacitor to withstand the peak currents of the NB-IoT transceiver without degrading the battery.

Fig. 3. Assembled Node (CoreBoard +SensorBoard + Antenna + Battery + Enclosure)

a) GPS Implementation Details

As mentioned earlier, the temporal synchronisation between the measurement nodes deployed throughout the structure under analysis constitutes a crucial factor in obtaining sufficiently accurate results. This synchronisation enables the application of OMA techniques traditionally employed for structural analysis as well as those of the highest innovation based on machine-learning and distributed processing, as referenced in Section II. Typically, the sampling frequency for civil engineering applications remains below 200 Hz. Therefore, proper synchronisation requires the coincidence of the time stamp of the measurements, in the order of milliseconds.

In order to calculate the temporal accuracy of the nodes, 100 different tests have been carried out with 2 nodes turned on at random instants of time, which, subsequent to the connection time (which depends on the signal coverage), take the current timestamp from the GPS-connected satellites and assign it to their internal Real-Time Clock (RTC). These nodes then print the current timestamp through the serial port at the moment of reception of a hardware interruption common to both nodes, which is generated at random temporal moments by a signal generator.

After 10 series of 10 tests each, the average time synchronisation (difference between the timestamps of tested nodes) obtained is 5.1ms, with 8ms and 4ms as the minimum and maximum synchronisation, respectively. Therefore, the results obtained enable the implementation to be made as a synchronisation method for the desired application.

Regarding current consumption, the A2235H module offers the “Hibernate” operating mode, which significantly reduces power consumption (27µA) compared to “Active” mode (36mA). This operation mode stores the identification of the satellites from which it obtains the temporary signal (while the device does not change location), thereby minimising the connection time (3s) to said satellites, as compared to an initialisation from shutdown (50.9s indoors and 31.3s outdoors) once each new measurement cycle begins. However, to evaluate the performance of the connection time in terms of energy consumed, the comparison of the energy consumption (3.6Vdc supply) is made by keeping the node in “Hibernate” state once the GPS signal is acquired until the next cycle of measurements, and by turning off the A2235H through a power gate after GPS connection until the new measurement cycle.

Given the aforementioned data, it is calculated that maintaining the A2235H module in hibernation mode is more efficient in terms of energy consumption just in case the measurement cycle reaches a periodicity of less than approximately 10 hours and 22 minutes outdoors or 17 hours and 46 minutes indoors. Generally, monitoring of civil structures is carried out when there is a change of context or relevant phenomena thereon, and hence it can be considered that daily monitoring at different moment (for example every 25h) generates a sufficiently updated health model [17][20], and therefore, it can be concluded that, in this application, it is more efficient to turn off the A2235H subsequent to GPS connection.

Furthermore, the use of the A2235H device georeferences the measurement points, which adds value to the measurements taken in terms of their metadata and, therefore, to the results obtained since they can be utilised in the structural analysis method.

Lastly, it should be highlighted how the integration of this device into the measurement nodes (at a cost of approximately 17€) exerts no significant impact (below 10%) on their total cost.

2) *Firmware design*

As can be observed in Fig. 4, the operation cycle is composed of two main states: Active mode (t_a), where the node performs the expected functionality, and Deep Sleep mode (t_{ds}), where it attains a very low power mode in order to save energy and maximise the battery life. Note that $t_{ds} \gg t_a$.

Although Fig. 4 shows a sequential diagram for a better understanding of the general operation of the node, these functionalities have been developed in parallelised tasks on the FreeRTOS real-time operating system, which is necessary to achieve the desired functionality while maintaining the strict time requirements of both synchronisation between nodes and the internal timing of each node. Since a robust and versatile solution is desired, a completely modular design is chosen, with functionally decoupled tasks. This allows said design to be adjusted and parameterised to the needs of objective structural monitoring.

As shown in Fig. 5, the firmware design has two Real-Time Clock (RTC) tasks for node timing: Alarm *A* wakes up the micro every operation cycle, while Alarm *B* sounds every 25s to feed the iWDT (internal WatchDog Timer), which guarantees that the microprocessor recovers from unforeseen events.

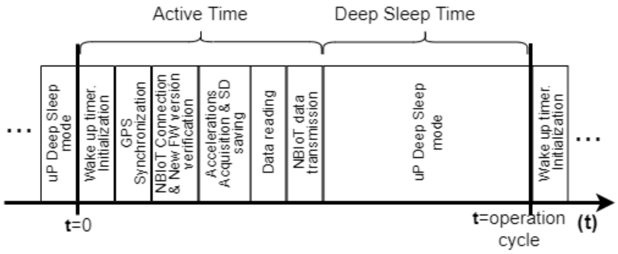


Fig. 4. Firmware functional timeline

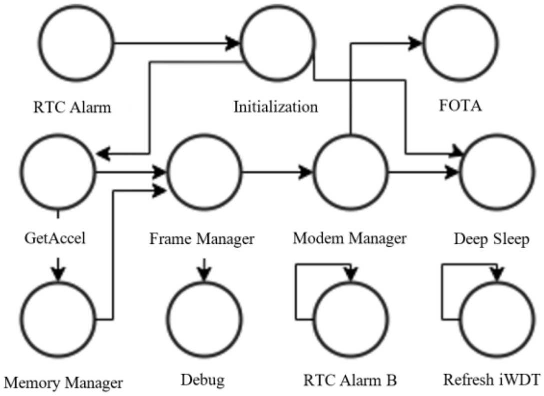


Fig. 5. Real-Time firmware tasks

The *Initialisation* task handles the task of activating the necessary peripherals to carry out the functionality (e.g., SPI, I2C, UART, and GPIOs) as well as that of updating the internal RTC to the GPS signal, which provides time synchronisation with the remaining nodes, by initialising the *Modem Manager*, which handles the tasks of transmitting the information through the NB-IoT module securely (TCP, SSL, and MQTT) and of launching the acceleration task (*GetAccels*). In parallel, these measurements are stored on the

SD card through the *Memory Manager* task so that the *Frame Manager* can encode and group them into superframes of 10 frames each to finally be sent to the *Modem Manager*.

All said information is sent according to the following superframe scheme: initially the *Node_Info* field is transmitted, which contains the unique identifier of the node, the identifier of the NBIoT SIM card and the embedded firmware version. Next, the data length and triaxial accelerations taken by the sensor are included in the *Sensor_Data* field, which is grouped in frames of 51 triaxial accelerations and in superframes of 10 frames, identified in the *Frame_Info* field. This results in a total of 510 triaxial acceleration samples per superframe (as max.), a value that matches the number of samples extracted from the SD card in each read iteration. Finally, a *CRC* code and an *End of Frame* (EoF) field are included to ensure the integrity of the information transmitted.

After sending all the measurements, the device will call the *DeepSleep* task that carries out the necessary configuration so that the microprocessor and its electronics pass onto the state of deep sleep for lower energy consumption.

It should also be noted that the node has a debugging task (*Debug*) which receives information from the rest of the tasks and sends it to the user through a UART port.

Finally, it is worth mentioning that the nodes have a task (*FOTA*) with the ability to update their firmware if required by the system user from the central server. This enables remote updates of deployed devices without the need to attain and access their locations.

B. NB-IoT Network

Since civil structures, dams, and historical heritage are not always placed in urban centres but may be found in rural areas or areas that are difficult to access, it is necessary to opt for a mature wireless communication technology with a sufficient coverage area instead of for local technologies, such as WiFi and Bluetooth, which would need a gateway in order to connect the devices with a remote server. In this respect, NB-IoT, which is a well-tested technology (market size greater than USD 1.7 billion is expected in 2026 [21]), is proposed as the best option since it is a network operated by the telephone companies that are in charge of maintaining the existing infrastructure. It therefore requires no additional deployment and is offered to users at economic rates (on the current date, 2023, this stands at 10€ every 10 years and 500MB [22], which suffices in the application presented herein).

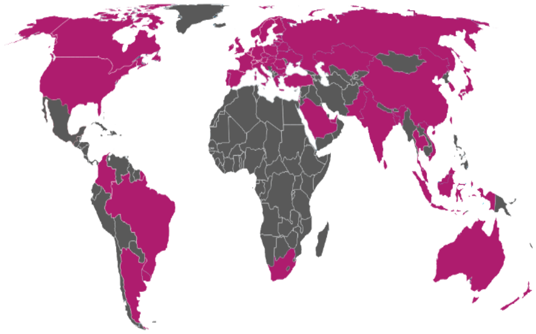


Fig. 6. NB-IoT cover map, data from [23]

Finally, as shown in Fig. 6, the GSMA organisation, which unifies most of the telecommunication operators with the industry and the communication sector, ensure a major level of coverage across most of America, Europe, and Asia. This guarantees the compatibility of the proposed solution across most of the world.

C. Private Server & Graphical Interface

The information sent by the nodes is received by the private server, which is responsible for storing, processing, and presenting it to the end user in a visually pleasing and intuitive way. For this reason, an implementation based on the deployment of microservices on a master operating system (Linux) and a virtual container system (Docker) has been chosen.

Four microservices have been deployed, in addition to the connection manager (Nginx) which enables communication (https) between them:

- Decoder: Since, for security reasons, the information from the nodes is sent encrypted in accordance with the system's data model, the first task to be carried out on the server involves its decoding and the validation of the truth of the received frame, which this microservice handles.
- Database: MongoDB technology has been used since it is a non-relational database that can facilitate its scaling (without modifications to that which has already been implemented), when the nodes, in particular, and the system, in general, could be scaled in terms of the services they offer.
- Back-end: A SPA (single-page application) tool such as Nodejs (JavaScript) has been selected, which offers its services to the front-end, as well as the management of security tokens and the implementation of a communication API through which memory access is made and data is offered to the remaining microservices.
- Front-end: The VUE progressive framework has been chosen as the stack for the creation of the user interface and all the features it offers.

Regarding the functionalities offered by the private server and its associated graphical interface, the following stand out: the management of user roles, the geolocation of devices, the management of thereof (e.g., registration, activation, and edition, the detailed presentation of the information (in table and graphical mode), downloading information (CSV and PDF), loading and deleting databases, and displaying and downloading the system activity log (Fig. 7).


Selected Sensor Data

Sensor Model: BMA400 Accelerometer
Location: White Tower
Magnitude: Accelerations
Device: AI-03

Custom time interval
Start
Start time
lun., 25 de abr. de 2022 17:37
End
End time
lun., 25 de abr. de 2022 18:37

Preset time interval

Fig. 7. Graphical User Interface. Detailed view of accelerations

The subsequent section presents the experimental results, beginning with the characterisation of the system, the methodology followed, and the validation of the results obtained.

V. EXPERIMENTAL RESULTS

A. *System Characterisation*

1) *Power Consumption analysis*

As mentioned above, the autonomy of the nodes is a fundamental aspect towards enabling their practical deployment in the field for the periodic and unattended monitoring of the structure (at least once a day) during the time required to amortise maintenance costs. In this work these characterization is carried out through current consumption and operation time monitoring using the Keithley 2540 SourceMeter. Fig. 8 shows the different phases of the operation of the nodes. Initially, GPS connection is made for time synchronisation, which supposes an average consumption of 36.24mA for 32.62s. Subsequently, the initialisation of the NB-IoT connection, the subscription to the necessary MQTT topics, together with the securitisation of communications (TCP and SSL) and the verification of whether the firmware update is necessary through FOTA consumes 41.8mA for 72.33s. Acceleration sampling consumes 9.15mA for the stipulated 420 seconds and the reactivation of the SIM7080 module needs an average current of 25mA for a time of 26.78s.

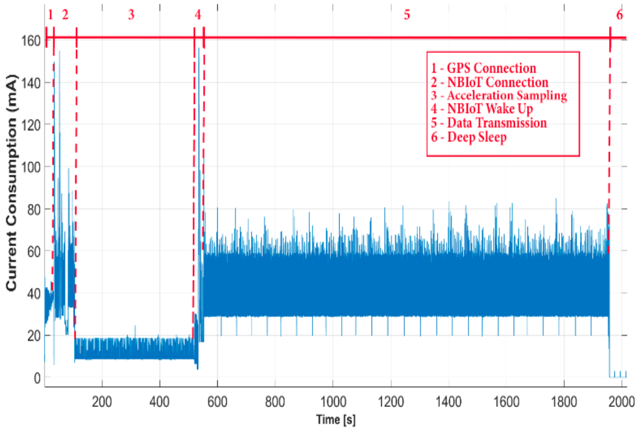


Fig. 8. Operation cycle current consumption

The data transmission period is made up of sending a total of 26 superframes with an average unit consumption of 40mA for 55.35s each. As commented in Section IV, these superframes are composed of 10 frames of 51 triaxial samples each. The node has an average consumption of 6μA in the Deep Sleep phase where the microprocessor is woken up periodically every 25s (for 0.33s with a current consumption of 1.65mA) to feed the WDT which protects the system from firmware crashes. Using the LSP 33600-20F battery (17Ah+20F supercap), these current consumptions result in an autonomy of 2 years and 4 months, which is considered sufficient to amortise the cost (13.10€) of this battery.

As can be observed, the greatest impact on the autonomy of the node is produced by the current consumption during data transmission: the greater the amount of data to be transmitted, the greater the consumption. Fig. 9 shows the evolution of node autonomy as a function of the number of superframes transmitted, where an exponential drop is observed due to the lower impact of the phases prior to transmission. Furthermore, the impact of time synchronisation for the various ranges of GPS connection times obtained is represented, where it can be observed how it is minimal (fewer than 25 days) regarding the autonomy of the node. This result, added to the fact that it is a key functionality, validates its use.

Fig. 10 presents the current consumption of a node that starts the firmware update process through FOTA and continues to operate with the new functionality. During the initialisation process, the node connects to the NB-IoT network, detects a new firmware version available, which is then downloaded and stored locally to proceed with the process of firmware updating. In the tests carried out, this process supposes an average current consumption of 30.2654mA and a time of 684s. Taking into account the capacity of the battery and the consumption of the node over the 2 target years (730 days @ 19.09mA/h), by performing one monitoring cycle per day (730*19.09mAh=13935.7mAh), a maximum of 532 remote firmware upgrades satisfy that requirement, which validates its application herein.

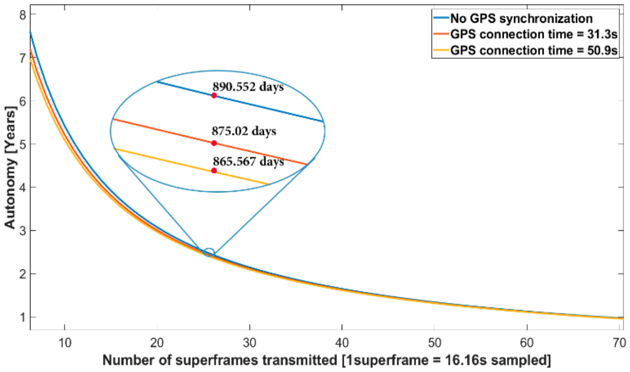


Fig. 9. Impact of data transmitted and time synch on autonomy

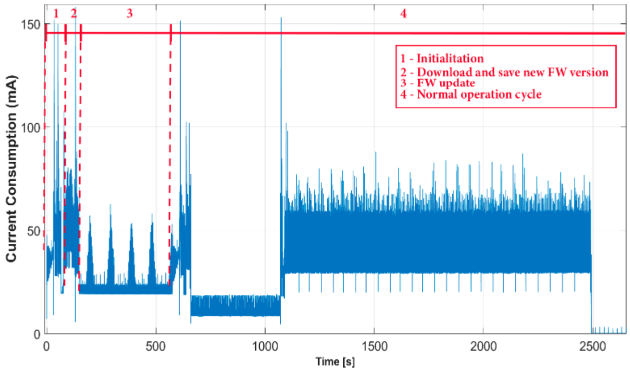


Fig. 10. FOTA & Normal operation cycle Current consumption

Therefore, this section demonstrates the viability of using both GPS time synchronisation and FOTA since the power consumption has a very low impact on the autonomy of the nodes and these functionalities are key aspects of a real deployment.

2) *System Comparison*

As has been commented above, the main goal of this work is the development of an SHM system which, while maintaining the necessary features to detect structural damage, minimises its cost as much as possible in comparison with commercial and traditional devices. A comparison of the capabilities of the high-performance commercial device GMS Plus6-73 marketed by GeoSIG, the system presented in [11] (the most similar system in the state of art to this work), and the node developed in this work is given in Table I.

As reflected in the comparison, the developed system has similar features to the commercial system in terms of security, synchronisation, data storage capacity, and degree of protection, and it reduces its price by up to two orders of magnitude and minimises its size by a factor of 21.5. Although it should be noted that even with a four-bit loss in resolution in its ADC, the results in the calculation of the resonance frequencies remain comparable, as can be observed in the following subsection. This work also offers long-range communication instead of a simple local connection of GeoSIG, and includes remote firmware updating and low consumption, which enables its installation and unattended operation.

TABLE I. COMPARISON OF FEATURES

Feature	*Traditional*	*Research solutions*	
	GeoSIG GMSPlus 6-73	*[11]*	*This Work*
ADC resolution	*24 bits*	*16 bits*	*20 bits*
Synchronisation	*GPS*	*No*	*GPS*
Storage Memo (max GB)	*SD card*	*µSD card*	*µSD card*
Power Supply (Vdc)	*15*	*3.6*	*3.6*
Battery	*7.2Ah*	*17Ah+Solar Panel*	*17Ah + 20F Supercap*
Security	*SSL+TCP*	*No (UDP)*	*SSL+TCP*
MQTT	*No available*	*No implemented*	*Yes*
Size (mm)	*296 x 225 x 156*	*-*	*151 x 80 x 40*
Weight (Kg)	*9*	*-*	*0.150*
Protection	*IP67*	*-*	*IP68*
Price (€/unit)	*15,000*	*-*	*157.13*
Autonomy greater than 2 years	*No (1 day)*	*Yes*	*Yes*
Wireless Communication	*WiFi*	*NB-IoT (Bands B1/ B3/ B8/ B5/ B20/ B28)*	*NB-IoT (Bands B1/ B2/ B3/ B4/ B5/ B8/ B12/ B13/ B18/ B19/ B20/ B25/ B26/ B28/ B66/ B71/ B85)*
Unattended periodic operation	*No*	*Yes*	*Yes*
FOTA	*No*	*No*	*Yes*

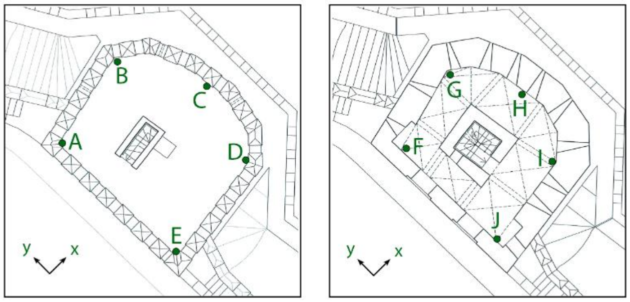
On the other hand, in comparison with [11], this work transmits 20-bit triaxial measurements instead of 16-bit measurements, which has a direct impact on power consumption and, therefore, system autonomy. However, although the autonomy is smaller, it does satisfy the requirement for 2-year autonomy as defined. Furthermore, this work offers two key features for remote structural monitoring (time synchronisation of the nodes and firmware update through FOTA functionality), which places it as the only device with these characteristics of the current state of the art.

B. Tests on the White Tower of the Macarena Wall

The White Tower belongs to the historical heritage of the city of Seville and is an Almohad fortified tower, built in mortar and brick with an irregular octagonal floor plan. It was built between the 12th and 13th centuries as part of the defences of the city wall of Seville. The White Tower is the only fortification that maintains its walled section.

The following figures present both the tower in its current state (Fig. 11) and the plan of the second (Fig. 12a) and first floors (Fig. 12b), together with the measurement points used.

Fig. 11. White Tower. Seville



a) b)

Fig. 12. White Tower and data acquisition plan. a) Second Floor; b) First Floor

Prior to data collection, a preliminary study of the White Tower was carried out with ANSYS. In this way, the first three vibration modes of the structure were identified (Table II). These results were very useful for the design of the experimental campaign. Since a torsional mode was identified, the measurement points were located away from the centre of rigidity of the tower. A total of ten points were selected (Fig. 12). On the other hand, the natural frequency of the first three modes of vibration was below 10 Hz. Therefore, the sampling frequency was fixed at 31.25Hz, thereby complying with the Nyquist sampling theorem ($f_s > 2 * f_N$, where f_s is the sampling frequency and f_N the maximum frequency of interest). Finally, a time window of 420s was adopted for each point. This value is justified since the length of the data series should lie between 1000 and 2000 times the fundamental period of the structure [24].

The methodology followed in tests, as an alternative to autoregressive methods, is analogous to that carried out in the EFDD studies [25][26] of SHM. One node was placed at point A and the other node at each of the other nine remaining points (B, C, D, E, F, G, H, I, and J). In this way, a total of nine tests were performed. Thanks to the GPS signal, the readings of both nodes are synchronised. Because the accelerometer is triaxial, 6 sets of accelerations are collected in each test. In accordance with the sampling frequency and the duration of the series, 13,260 measurements are taken on each axis. This procedure was made simultaneously with two GSM Plus GMS6-73 accelerographs, whereby measurements were taken in parallel with the nodes of this work, that is, under the same conditions.

Once the measurements were taken, the estimation of the dynamic properties of the structure were determined by the application of OMA. In particular, the EFDD method was used in the ARTeMIS Software tool.

For each test, it is possible to estimate the spectral density matrices for each frequency from the acceleration data. The next step consists of the SVD decomposition of these matrices, thereby obtaining the singular values. To ascertain the natural frequencies of the structure, it is necessary to take the average the singular values of all the tests. These averaged singular values are shown Fig. 13 and Fig. 14, which correspond to the data taken with the GSM Plus GMS6-73 units and with the devices described in this work, respectively.

As can be observed in Table II, Fig. 13, and Fig. 14, the results offered by both systems are similar for the three modes detected, obtaining a maximum difference of 3.51% in the case of Mode 2, which is an irrelevant percentage in terms of detecting building damage [27][28].

Once the results obtained achieve sufficient precision to validate the operation of the nodes, it is important to consider that structural damage generally manifests itself with a decrease in the natural frequencies of the structures, and hence stability of the measures is crucial. In this respect, the experiment was repeated, obtaining a standard deviation of less than 0.5% with respect to the frequencies shown in Table II, thereby validating the behaviour of the developed nodes.

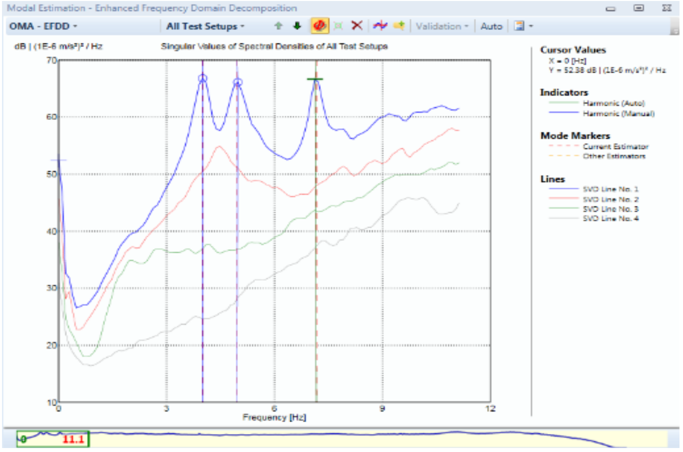


Fig. 13. White Tower behaviour. GeoSig GSMPlus results

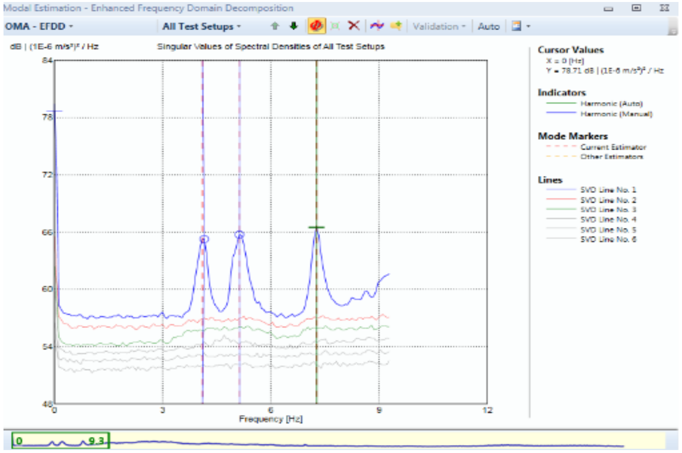


Fig. 14. White Tower behaviour. Results of this work

TABLE II. WHITE TOWER NATURAL FREQUENCIES DETECTED. SYSTEM COMPARISON

Mode	GeoSIG GSMPlus (Hz)	This work (Hz)	Difference (%)
1	4.004	4.104	2.50
2	4.957	5.131	3.51
3	7.166	7.267	1.41

VI. CONCLUSIONS

This paper presents the design and validation of a complete and scalable IoT system for SHM applications, consisting of terminal nodes of very low power and a web platform with natural frequency detection algorithms. The proposed system holds several advantages over existing SHM systems on the market and in the literature. On the one hand, in addition to being a low-cost, small-size, and low-power scalable system, it implements a time synchronisation mechanism between nodes based on the GPS signal thereby permitting the application of structural analysis techniques, both traditional and current, based on machine-learning techniques. On the other hand, FOTA capability enables the deployment and maintenance of the firmware of the nodes without the need to access the installation points. These capabilities have been validated through energy consumption analysis and it has been concluded that the autonomy of the nodes exceeds the requisite 2-year duration allowing more than 500 firmware updates through FOTA without compromising the desired autonomy. Moreover, the developed solution uses secure connections (SSL and TCP connections) and MQTT transmissions, which guarantee its integration into current IoT systems like Amazon Web Services or Azure. This development is supported by an IoT management platform composed of a private server with architecture based on microservices with visualization and processing capacity for the data transferred from the terminal nodes.

Finally, the proposed IoT system was validated in a real historical building in the city of Seville: the White Tower. To evaluate the performance of the IoT system in the field, the acceleration tests were performed simultaneously with calibrated commercial equipment. Experimental results show the detection of the natural frequencies of the structure with a maximum error of 3.21% (less than 0.5% of standard deviation) with respect to the reference equipment, but reducing its cost by two orders of magnitude and guaranteeing autonomous operation for two years while providing daily measurements. It can therefore be concluded that all these capabilities place the work developed herein as unique in the current state-of-the-art tools for structural damage assessment.

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