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Structural health monitoring of a damaged church: design of an integrated platform of electronic instrumentation, data acquisition and client/server software

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SUMMARY

A practical view is provided on the integration of electronic instrumentation, data acquisition, and software development systems applied to the analysis of pathological structural processes. This system will enable researchers to remotely monitor constructions; compile a register of historical data, creating files for postprocessing; and establish computer-based protocols for evaluation of information, defining automatic alarms when the monitored data exceed preset limit values. This integration is based on the implementation of a remote terminal unit architecture in an industrial PC along with some other elements, namely, the following: suitable data acquisition cards for the type of sensors used, which continuously collect the data the sensors gather; the installation of an application server that periodically communicates with the system, extracting data while guaranteeing persistence; and finally, a web server, which provides remote access to both the data themselves and the system configuration, using a client application developed in JavaFX, a platform for developing rich Internet applications. As an example of the integration, the architecture of a system deployed in a Church in Comillas, Spain, is shown. The work carried out related to the register of existing damage is reported in order to explain the choice of the zones for deployment of the monitoring devices as well as the tasks involved in the installation of the sensors and other devices. Finally, the evolution is presented of the measurements taken during more than 1.5 years of monitoring, as well as their validation through comparison with those obtained by discrete *in situ* measurement. Copyright © 2015 John Wiley & Sons, Ltd.

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1. INTRODUCTION

The conservation of existing buildings is a fundamental principle in the cultural life of modern societies. In economic terms, the building rehabilitation and maintenance market is one of the most important economic sectors in building field, especially in the most developed societies. For instance, in Europe, in 2010, rehabilitation and maintenance was a major market, accounting for 28% of construction output with a value of €332, 000, 000 [1], and in the USA, this sector also accounts for an important fraction of the construction market. In addition, there are many other factors that indicate that the rehabilitation market has high growth potential in many countries: the growing social awareness that preservation and enjoyment of the building heritage has acquired, the favorable prospects offered in

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certain areas by the cultural sector as an engine for activity (cultural tourism), the progressive aging of existing housing, and so on. Moreover, the rehabilitation sector is a key topic in terms of sustainable urban growth: promoting lower energy consumption (in contrast with demolition and new work), consuming less material than new construction work, and so on.

The diagnosis of ancient buildings supposes important challenges from the point of view of its evolution under field conditions. This is because of the complexity of their geometry, the variability of the properties of traditional materials, the different construction techniques that are commonly used, lack of knowledge about existing damage, and how certain actions affect the constructions throughout their life [2]. Due to this, the architectural heritage buildings are subjected to a number of difficulties in diagnosis and restoration under field conditions [3,4]. As a result, understanding, analysis, and repair of historic buildings remain among the most important challenges of modern technicians [5].

Interventions in old constructions, given their fragility, require precision and detail in developing a rigorous previous diagnostic study, which provides the basis for decisions about the intervention techniques that should be adopted [6–8]. In line with the article's topic, the monitoring systems undoubtedly contribute to knowledge of the evolution of specific processes [9–11] before, during, or after an intervention. One of the most frequently cited studies is medieval structures of Pavia, Italy, where, after the collapse of the Civic Tower in 1989, public safety was guaranteed based on a constant observation and online monitoring [12]. Other work in this field includes References [13–17].

In addition, upon completion of an intervention or when immediate action is not warranted, it is important to know the evolution of certain parameters, based on a preventive and not palliative maintenance strategy in order to provide timely warning of the need for possible future intervention [18]. In this sense, different countries have begun to develop strategies based on preventive maintenance, given that this leads to resource optimization and cost savings (rehabilitation is more technically and economically efficient than repairing, and moreover prevents damage). This also reassures society of the dedication of the authorities to the preservation of the cultural heritage of a region.

Within this introductory framework, and in the particular case of the Modernist Church of the Comillas Seminary, Spain, the article aims to present a practical perspective about the integration of systems of electronic instrumentation, data acquisition, and development of software applied to the monitoring of pathological structural processes in damaged historic buildings. This integration is based on implementing a remote terminal unit (RTU) architecture in an industrial PC, along with data acquisition cards suitable for the deployed sensors, which continuously collect the data acquired by the sensors, and installing an application server, which periodically communicates with the system, extracts the data, and stores them permanently in a database. Finally, a web server enables remote access to this information through a client application developed in JavaFX.

To achieve this, firstly, the record of existing damage in the church is presented with the aim of providing input data to choose the zones in which to deploy the monitoring devices, selecting the areas where the damage is greatest. Next, the previously mentioned integration of systems of electronic instrumentation, data acquisition, and software development (server and client applications) is described. Then, the work related to the installation of the monitoring points and the logistics of the data collection and posterior data treatment is presented. Finally, the evolution of the measurements collected over a period of 1.5 years is detailed, and these data are validated by comparison with the data obtained through discrete *in situ* monitoring.

2. RECORD OF THE EXISTING DAMAGE IN THE CHURCH

The modernist building of the Comillas Seminary was constructed at the end of the 19th century (Figure 1(a)). It has a rectangular floor area of 100 m × 65 m, being built around two cloisters, of approximately 35 m × 25 m, which surround a central volume where the most interesting architectural and artistic elements are found: the entrance hall, the principal staircase, the main hall, the sacristy, and the church. Figure 1(b) and Figure 1(c) illustrate the intrados and the extrados of the church's domes, before the interventions made in the building since 2007. While Figure 1(d) shows the current interior's underpinned construction, Figure 1(f) shows the tie rods that exist between the opposing buttresses.

After arduous onsite data-taking work from August to September 2012, a total of 41 plans were drawn up showing the recorded damage, classifying the cracks depending on their width, accompanying

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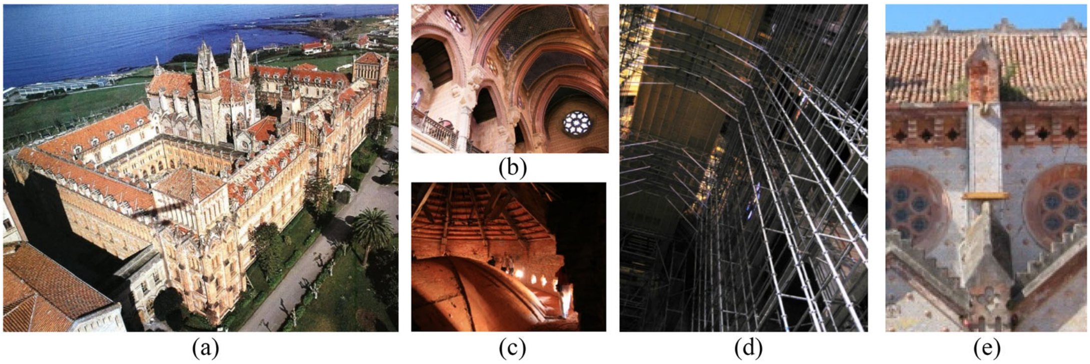

Figure 1. (a) Overview of the 'Seminario Mayor de Comillas' before the interventions carried out in the building after 2007. Intrados (b) and extrados (c) of the domes of the church. (d) Current state of the underpinned structure. (e) Tie-rods between buttresses.

them with a photographic record of their existence. Thus, maps of the cracks were created, with associated photos, corresponding to the zones of arches and buttresses, domes, interior walls, and exterior walls (facades). As an example, Figure 2(a) shows one of the sections registered in the plans with the previously mentioned cracks, while Figure 2(b) illustrates one of the plans with photographic information. The principal damage is located between arches 3 and 4 and in the zone of the narthex of the church.

3. INTEGRATION OF ELECTRONIC INSTRUMENTATION, DATA ACQUISITION, AND SOFTWARE DEVELOPMENT

The integrated platform presented is based on the installation of the following:

- An industrial PC, with data acquisition cards suitable for the type of sensors employed, performing continuous data collecting.
- An application server, periodically communicating with the system, constantly extracting data.
- A web server, enabling remote access to these data
- A desktop application, developed in JavaFX, a new platform for developing rich client and Internet applications, with a user-friendly interface, enabling remote access in real time to data, status, alarms, offset adjustments, and so on.

Supervisory control and data acquisition system (SCADA) refers to the combination of telemetry and data acquisition. SCADA encompasses collection of the information via one or several RTUs, transferring it back to a master terminal unit (MTU) via a communications system [19]. While the MTU is the heart of the SCADA system, usually located in a control room, an RTU is a microprocessor-based device, located in a remote field installation and connected to sensors, transmitters, or processing equipment for the purpose of remote telemetry and monitoring [20]. The MTU is in charge of requesting the information gathered by the RTUs, and interfacing with the application server. The RTU operates as a data acquisition and control unit, interfacing with local equipment through physical input/output connections. Its main purpose is monitoring and controlling equipment by gathering and uploading data from the processing equipment installed at remote locations. RTUs meet the challenges of remote monitoring and control by optimizing data collection and transmission and by managing data communication so that a large number of remote devices can communicate within a system using cost effective remote communication links.

3.1. Implementing a remote terminal unit architecture with Ethernet for control automation technology

Taking into account the reduced funding devoted to damage control, a decision was made to monitor the most critical areas in the church. Figure 3 shows the areas selected and the location of the different units in the integrated platform within the church layout.

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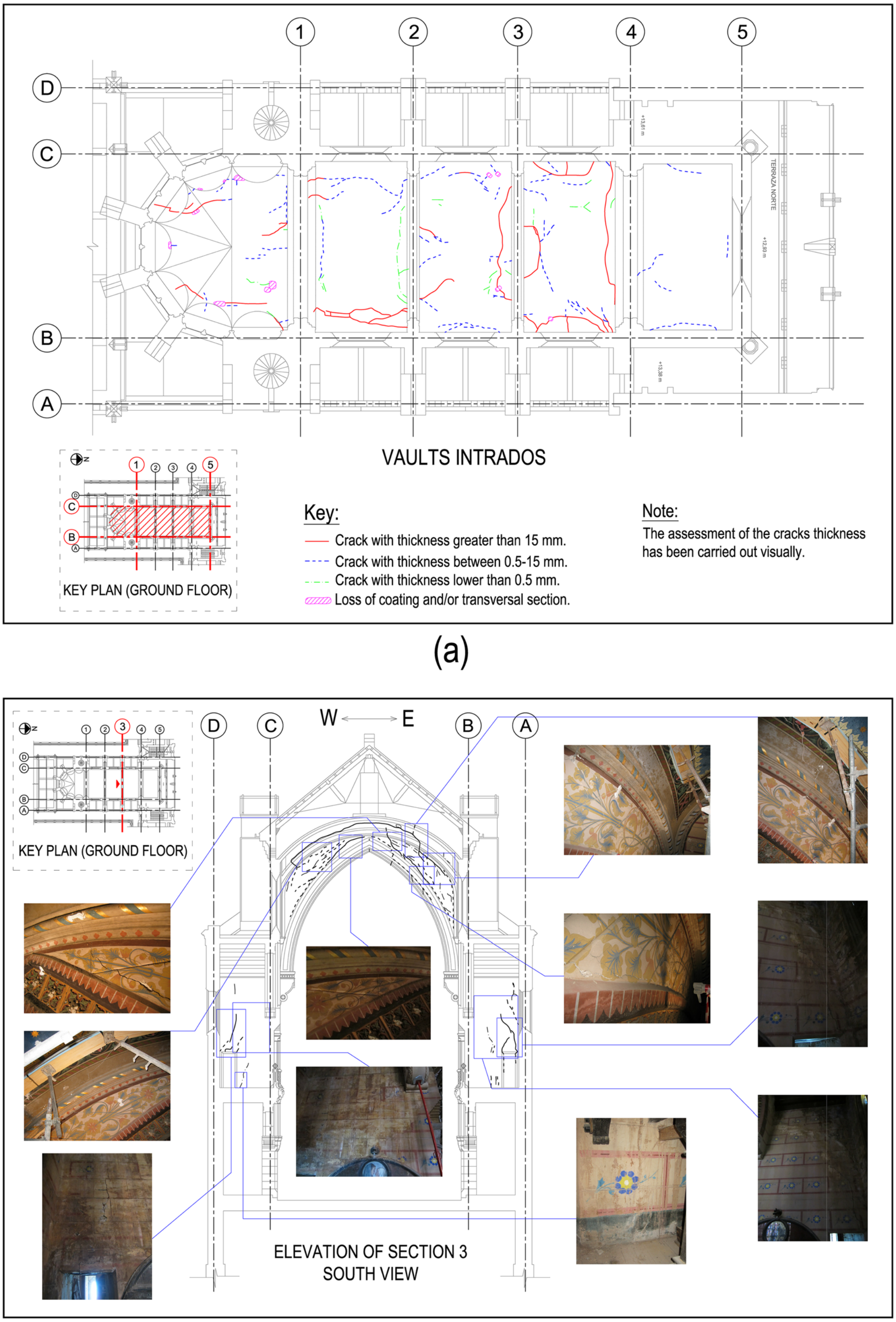

Figure 2. (a) Example of crack projection onto plan in the domes. (b) Example of plans of the photographic report (arch and buttresses of section 3, southern view).

The MTU used is the industrial PC C6920 [21], designed for installation in the control cabinet. The compact case shown in Figure 4 is equipped with a 3.5-inch motherboard for Intel® Core™ Duo or Core™2 Duo, 2 GB DDR3 RAM, 80 GB hard disk and Intel® GMA 4500MHD graphic adapter (manufacturer: Intel Corporation, Santa Clara, California, USA). All PC connections are located on

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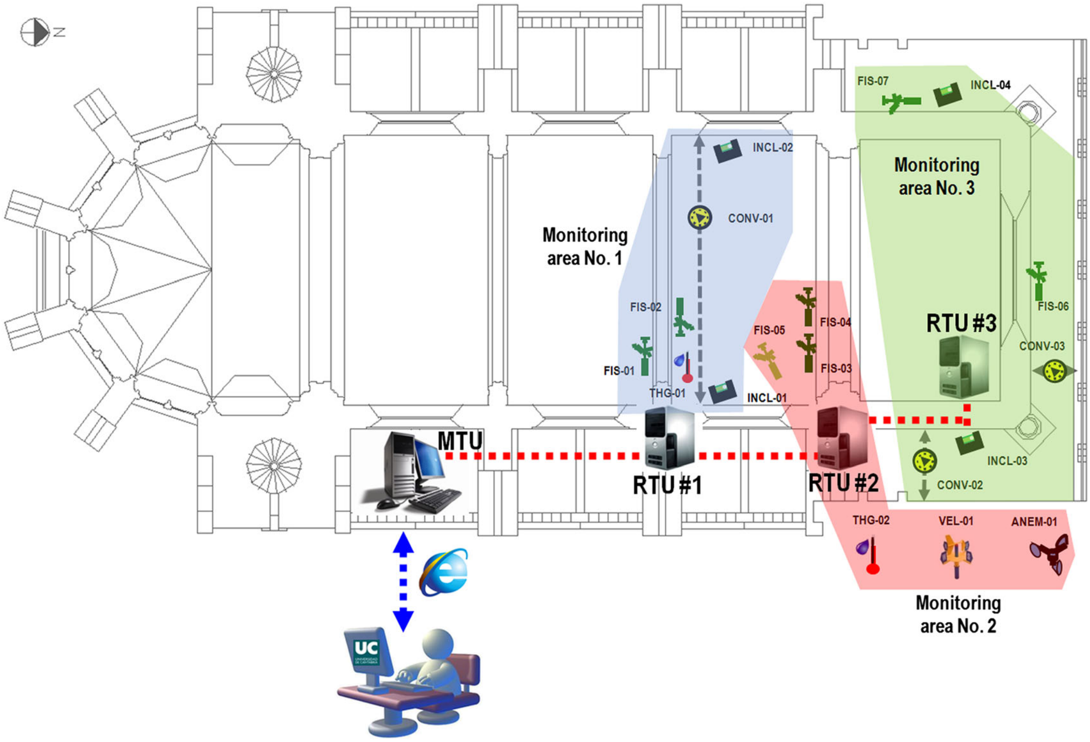
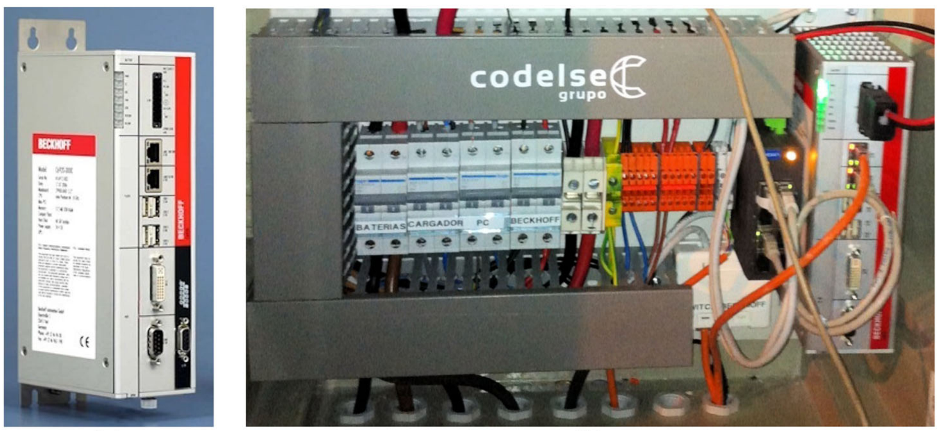


Figure 3. Selected areas of study and sensors distribution. RTU, remote terminal unit; MTU, master terminal unit.



(a) (b)

Figure 4. Control cabinet with industrial PC C6950, (a) unmounted and (b) mounted.

the front of the housing. The unit is cooled by internal cooling fins and an easily exchangeable fan cartridge at the bottom of the housing. The top socket connects the 24 V_{DC} power supply. Two RJ-45 connectors enable 10/100/1000BASE-T LAN connection for Ethernet or Ethernet for control automation technology (EtherCAT). There are four USB 2.0 interfaces, a digital visual interface connection for video signal and finally, on the bottom, a serial COM1 type RS232 interface and a fieldbus interface. A compact flash card or hard disk can be connected on the slots hidden behind the front flap.

Given that the central control cabinet is not usually near the sensor emplacement, RTUs must be used in other distribution cabinets. Three EtherCAT couplers EK1100 [22] are used as RTUs (Figure 5(a)). Basically, one terminal station consists of a coupler, any number of EtherCAT terminals, and a bus end terminal (EL9011) (Figure 5(b)). The coupler converts the remote measurements from Ethernet 100BASE-TX to E-bus signal representation with a minimal latency. The coupler supplies the

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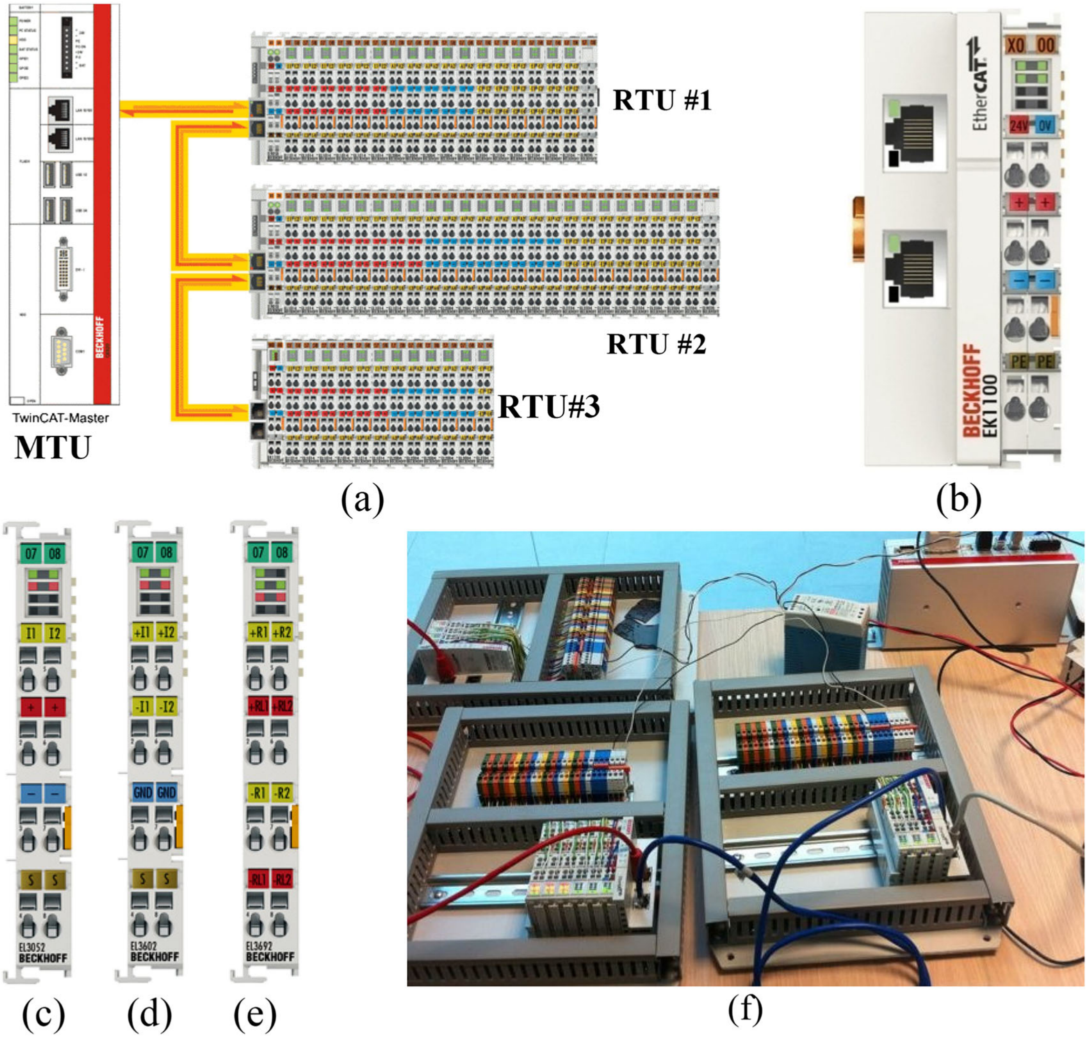

Figure 5. (a) Tree topology network master terminal unit (MTU)–remote terminal units (RTUs). (b) Ethernet for control automation technology coupler EK1100. Analog input terminals: EL3052 (c), EL3602 (d) and EL3692 (e). (f) Procedure for attachment to mounting rail.

connected terminals with the necessary E-bus current for communication. The coupler can supply a maximum of 5 V/2 A. Power feed terminals (EL9410) must be integrated if more current is required. The distance between stations should not exceed 100 m.

Each coupler has several terminals connected to the right hand side of the fieldbus coupler, once this has been attached to the mounting rail. When monitoring sensor values, analog input terminals (EL3xxx, Figure 5(c)–(e)) will mainly be used. With one, two, four, or eight input channels, the signal can be voltage (EL3602, −5 V to 5 V), current (EL3052, 4 to 20 mA), or resistance (EL3692, 10 mΩ to 10 MΩ), in all cases with 24-bit resolution. Figure 5(f) shows how the three stations are manufactured, with the assembly of the different terminals with their coupler in each RTU, and the testing of the network with the MTU and the three RTUs, according to the required configuration (Figure 5(a)).

3.2. Sensors

Table I lists the sensors used, while Figure 6(a)–(d) shows some of them placed *in situ*.

Once the RTUs are installed in the cabinets anchored to the wall, Figure 6(e), the sensors are carefully placed (Figure 3), and all the wiring is installed from the sensors to the RTUs and the EtherCAT connection from these to the MTU. The EtherCAT distributed network collects all the

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Table I. Installed sensors.

Sensor	Model	Manufacturer	Abbreviation
Servo-inclinometer	SX41100	Sensorex	INCL
Crackmeter	LVDT V02505SAN3	Solartrom Metrology	FIS
Tape extensometer	WS10-50-R1K-L10-SB0-D8-HG	ASM GmbH	CONV
Thermo-hygrometer	P18	PCE-Ibérica	THG
Anemometer	3R KYWS	Darrera	ANEM
Wind vane	3R KYWD	Darrera	VEL

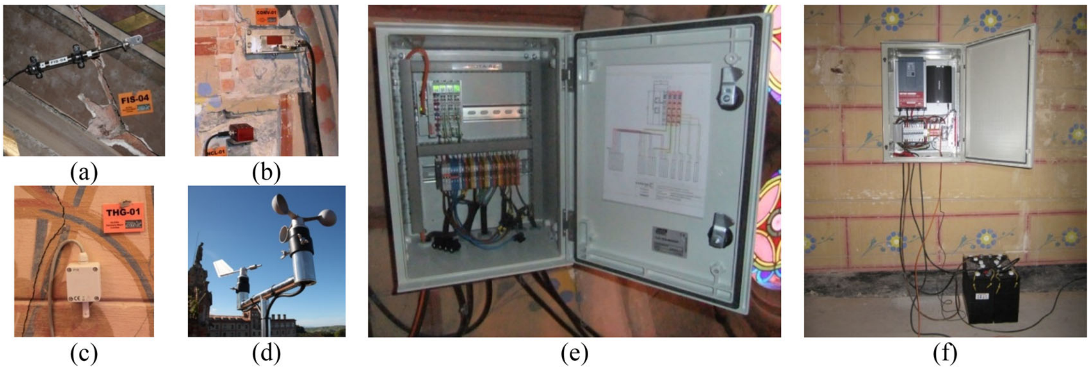

Figure 6. Examples of sensors deployed. (a) Crack meter FIS-04. (b) Tape extensometer CONV-01 and servoinclinometer INCL-01. (c) Indoor thermo-hygrometer THG-01. (d) Wind vane and anemometer. (e) Remote terminal unit #2. (f) Master terminal unit with auxiliary batteries at the bottom.

data from the sensors through the terminals in the RTUs and passes them to the MTU, where the software [23] scales the raw values to the corresponding units and magnitudes of their physical values, adding required offsets, setting alarms due to values outside the range, and so on. Moreover, to enable access to and extraction of all the data from the MTU, a specific server will be installed in another industrial PC, with remote access, and with the right protocol, and the two will be connected. Both PCs have an emergency power system consisting of auxiliary batteries, Figure 6(f), with autonomy for one week.

3.3. The user interface

A Java server is installed in this second PC, and a three-tier architecture is implemented, under the classic model-view-controller paradigm MVC/2 [24].

The designed user interface application runs on a desktop PC. It enables remote access to the installation to gather and view in real time the data collected by the sensors through the different RTUs (Figure 7(a)). It also allows the retrieval of data within a given range of time, to plot charts (Figure 7(b)) or store it (comma-separated values format) for further processing. Only top-level users can access these services, with certain limitations, according to their assigned roles. They can modify sensors' scale settings, define ranges of validity of the registered data, and create alarms when the data are outside these ranges, so selected users will receive a notification by email. Designed with the JavaFX 2.2 platform, and updated to the new Java 8 version [25], it provides a lightweight, hardware-accelerated native Java graphic user interface platform to provide remote access to the application on the server side.

4. OBTAINING DISCRETE *IN SITU* MEASUREMENTS

To complement the continuous sensors deployed, and with the aim of providing contrast measurements to the electronic sensors, a total of 22 observation points were installed for discrete *in situ* monitoring, which in turn limited the cost of the system deployed. Of these, 16 were aimed at evaluation of crack

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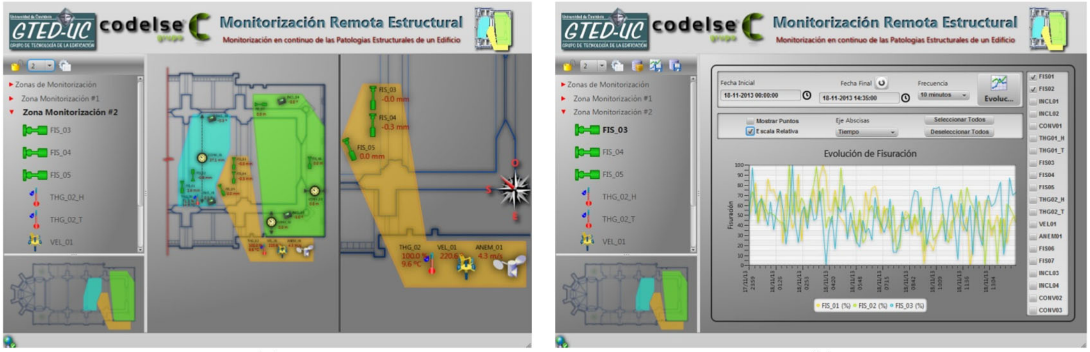


(a) (b)

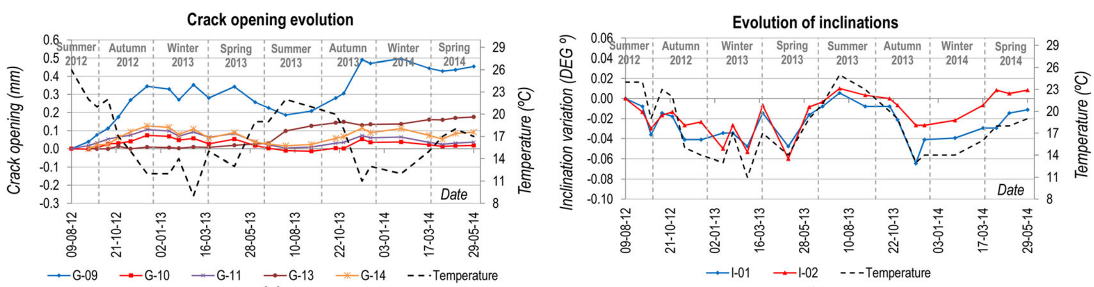
Figure 7. User interface. (a) Real-time data monitoring. (b) Chart visualization.

opening/closing through the use of a deformation meter (manufacturer: Mayes Instruments Limited, Windsor, Berkshire, UK with a 200 mm measurement range), while the other six were inclinometer plates to detect loss of verticality of the walls with the aid of a portable inclinometer (manufacturer: Meggitt (Sensorex), Archamps, France).

An equilateral triangle formed by 3 monitoring points was located on each crack selected (Figure 8(a)) so that by measuring the distance among them, the variation in the width of the crack and the possible displacement between the edges could be evaluated. For the inclination measurement, a stainless steel plate was installed at the chosen locations and equipment was placed on it to record the angle between the apparatus and the reference plane of the metallic plate (Figure 8(b)). In addition, for each measurement point and time, the temperature was recorded with the aim of assessing the influence of temperature variations on the measurements.

(a) (b)

Figure 8. (a) Manual monitoring points of crack G-013. (b) Register of the inclination I-02 through portable equipment.



(a) (b)

Figure 9. Examples of evolution graphs. (a) Cracks monitored in the influence zone of Arch 3 (+ indicates opening of the crack) and (b) inclination registered in the East load bearing wall at the level of the lateral oratories (+ indicates loss of verticality toward the inside of the wall).

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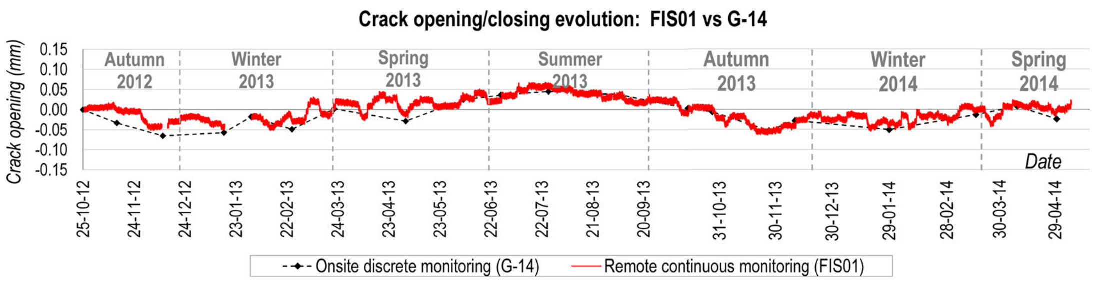
5. EVOLUTION AND VALIDATION OF THE RECORDED DATA

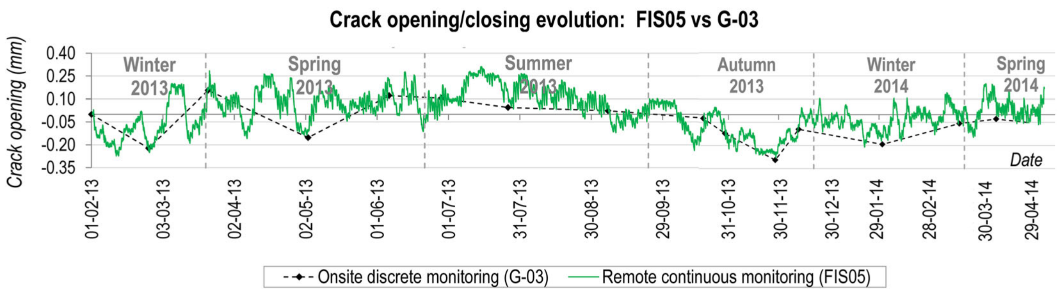
In order to illustrate the functionality of the integration of the electronic instrumentation, data acquisition and software development system, the evolution of the recorded measurements is shown, obtained through discrete in-situ monitoring and by continuous remote monitoring over more than 1.5 years.

In accordance with the methodology used, and bearing in mind the evolution of movement recorded through discrete *in situ* monitoring since the beginning of August 2012, in relation to the opening of cracks, it can be seen that the measurements recorded manually remain almost insignificant given that the width of the movements is in no case greater than 0.5 mm. Moreover, it should be remarked that the variations in the crack width relate to the thermal gradient existing between the measurements (Figure 9(a)). After a year of taking data, the residual width increases recorded for most of the cracks are of the order of hundredths of millimeters. The largest value recorded corresponds to crack G-09 with 0.170 mm of residual crack opening.

In relation to the *in situ* monitoring of inclinations, the inclinometer plates registered very low angular variations. In a similar way to the case of crack widening, the evolution of inclination recorded



(a)



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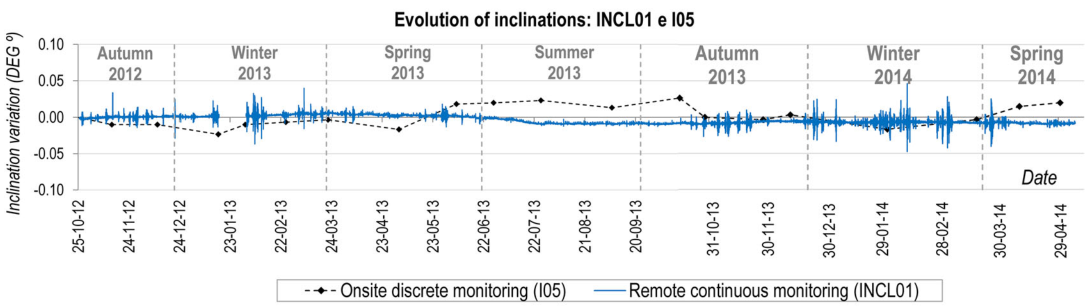

(c)

Figure 10. Examples of evolution graphs registered by the continuous sensors. (a) Continuous opening of cracks through the crack meter FIS01 (− indicates opening of cracks) and comparison with the manually obtained value (G14). (b) Opening of cracks registered by the FIS05 emplaced in the extrados of a dome (− indicates opening of cracks) and comparison with the measurement obtained manually (G03). (c) Inclination registered by the INCL01 located on the East load bearing wall (− indicates loss of verticality toward the outside of the wall) and comparison with the measurement obtained manually (I05, it should be remembered that the precision of the portable inclinometer for manual monitoring is two hundredths of a degree).

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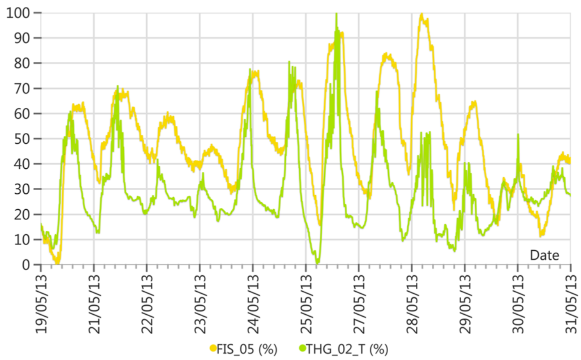
appears to be related to the temperature fluctuations registered among the different times of measurement (Figure 9(b)).

In relation to the online management of the data recorded in the continuous monitoring, as an example, Figure 10 shows some of the crack and inclination evolution curves registered by the sensors since their installation. Similarly, as a comparison, the measurements taken manually on the different visits to the building, at monitoring points adjacent to the sensors deployed, are also shown. The small differences in the graphs, more marked in the case of measurements to detect loss of verticality of the walls, may be associated with the manual systems precision being, logically, smaller than the sensors (for example, the portable inclinometer's precision is 0.02°, whereas the sensor's is 0.0006°). These differences might also be motivated by possible errors associated with the placement of the manual devices on the points to measure crack opening or above inclinometer plates. However, it can be seen that the fit of these measurements is quite good, which validates the reliability of the electronic system.

In relation to the behavior recorded by the continuous sensors, it should be highlighted that the measurements recorded by the crack meters installed under the domes (Figure 10(a)) are still of the order of hundredths of millimeters (after a year of monitoring, they only show a width increase of around 0.140 mm registered for FIS-04). The crack meter FIS-05, located over the domes, registered larger aperture widths over the monitoring period (Figure 10(b)), although, after 1 year of monitoring, it had undergone practically no change (0.008 mm). The cause of this oscillation is the direct effect of exterior atmospheric changes, due to the existence of ventilation gaps for the covered space (Figure 11(a)). Additionally, and as is also shown by the manual monitoring points, the opening and closing of the cracks is associated with the thermal variations undergone by the material (contractions and dilatations) (Figure 11(b)). The angular variation recorded by the inclinometers has shown only small variations since their placement (Figure 10(c)).

(a)



(b)

Figure 11. (a) Influence of exterior environmental conditions on the evolution of FIS-05, due to the existence of ventilation holes in the roof space. (b) The crack where FIS-05 was installed (– indicates opening of the crack) opens because of the decrease in temperature, as it closes with the inverse conditions (ordinate axis related to each sensor).

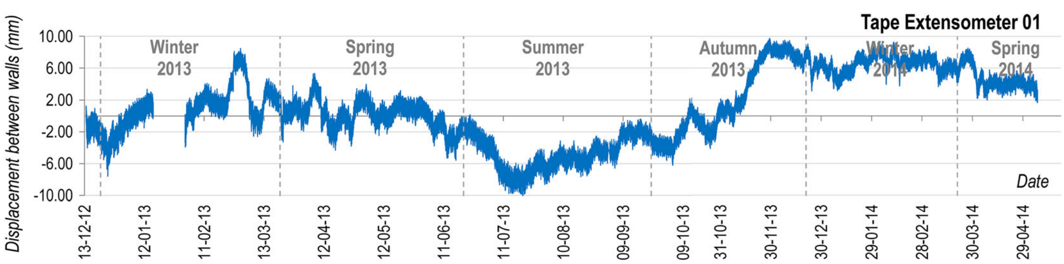


Figure 12. Extensions registered by the tape extensometer (CONV01) located beside Arch 3 (– indicates the approach of the walls).

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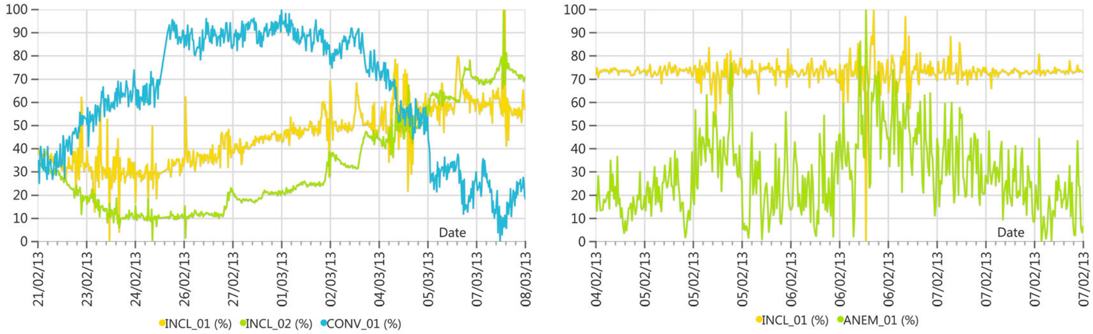
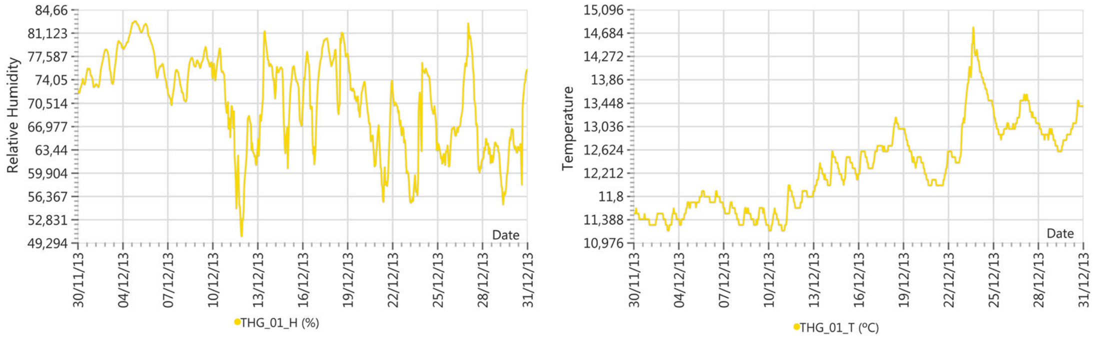


(a) (b)

Figure 13. Examples of relations among the sensors installed (ordinate axis related to each sensor). (a) As the servo-inclinometers (+ indicates inclination toward the inside of the wall) register values of loss of verticality toward the inside of the walls, the tape extensometer reflects a shortening and vice versa. (b) Influence of the wind on the walls reflected in the register of the servo-inclinometers through instantaneous vibrations and their subsequent attenuation.



(a) (b)

Figure 14. Environmental conditions, temperature (a) and humidity (b) registered inside the church (THG01) during December 2013.

The greatest displacement registered by the tape extensometer (CONV01), with respect to its initial position, was an extension of approximately 9.5 mm in November 2013 (Figure 12). As can be appreciated, this displacement over a distance of 9.7 m between the anchor points is not significant.

Based on the interpretation of the readings of the sensors installed, the correct evolution of their measurements could be verified. Thus, Figure 13(a) illustrates the coherent behavior between the evolutions in the inclinations of the walls, at the anchor points of the tape extensometer, and the elongation it recorded. As the servo-inclinometers register values of loss of verticality toward the inside of the walls, the tape extensometer reflects a shortening and vice versa.

In other cases, the effects of wind actions on the behavior recorded by the sensors could be seen. Thus, occasionally greater values of inclination were measured than those that were habitually registered, which could be associated with instants when significant wind speeds were recorded (related to high winds). Figure 13(b) shows, as an example, how the influence of the wind on the walls is reflected in the register of the servo-inclinometers (vibrations that are gradually attenuated).

Finally, Figure 14 shows a temperature and humidity evolution graph of the inside of the church.

6. CONCLUSIONS

It can be concluded that remote monitoring systems will unquestionably contribute to the knowledge of the evolution of certain processes in historic buildings. This tool is of particular interest for developing a preventive maintenance strategy.

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Throughout the practical application developed at the Modernist Church of the Seminary in Comillas, Spain, the authors have proven the versatility of the implemented system, both in terms of hardware: master, remote units, terminals, and sensors and in terms of software: application server, web server, data persistence, and user interface. The system is modular and scalable, which means it can be easily modified, removing or adding new RTUs, or adding more sensors and their data acquisition cards if new areas are incorporated into the study. Furthermore, the software can be easily adapted to future changes, and while it runs on desktops at the moment, it can be ported to other platforms (smartphones and tablets), to provide mobile access to the system.

The client application developed with the latest technology in user environments has proved that user-friendly industrial monitoring applications can be created, which are attractive to the user, with simple intuitive management while providing all the functionalities required by the project.

The remote monitoring system deployed has provided a centralized monitoring tool for the parameters of interest. The suitability of combining a continuous electronic monitoring system with a discrete manual one should also be highlighted, not only to favor the increase in the number of points being monitored at a reduced cost but also to provide contrast measurements for comparison with the electronic sensor ones. It has been experimentally verified that the fit of discrete *in situ* measurements is quite good, which validates the reliability of the electronic system. The small differences in the graphs may be associated with the manual system's precision being smaller than the sensors' and with possible errors related to the placement of the manual devices at the measurement points. Additionally, both in continuous electronic and discrete manual monitoring, the opening and closing of the cracks is associated with the thermal variations undergone by the material (contractions and dilatations).

Finally, in relation to the variables monitored in the Church of the Seminary, after a little more than 1.5 years of monitoring, it can be concluded that the monitoring points have not registered significant movements, which seems reasonable given the support structures existing in the body of the church to confront vertical action (Figure 1(d)) and the tie rods existing among the buttresses to counteract the horizontal forces of the main arches (Figure 1(e)). In the future, the authors intend to present the results of the monitoring carried out during the church's rehabilitation work and those obtained after the finalization of these. The work is scheduled to begin by the end of 2014.

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