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https://www.tandfonline.com/doi/full/10.1080/15583058.2022.2069062

JOURNAL: International Journal of Architectural Heritage
Conservation, Analysis, and Restoration

Integration of laser scanning technologies and 360º photography for the digital documentation and management of cultural heritage buildings

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Abstract

This work presents a critical overview and an integrated application of two of the most promising digital technologies for the conservation of heritage buildings. On the one hand, the work discusses and evaluates the laser scanning technology and its current applications to preserving heritage buildings. On the other hand, the fundamentals and recent practices in 360º imaging are analysed. Finally, both technologies are integrated in two emblematic study cases, i.e. a large Neo-Manueline church in Portugal and a small Romanesque church in Spain, with the aim of creating geo-referenced enriched digital models and supporting the design of a proper preventive conservation plan. The large differences in terms of shape and extension of

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the investigated buildings demand the use and combination of different laser scanning and 360º imaging technologies in order to provide the best digital product at the least cost.

Keywords: cultural heritage virtualization, preventive conservation, historical constructions, terrestrial laser scanner, wearable mobile mapping system, 360º camera, web-GIS.

1. Introduction

Built cultural heritage entails a wide diversity of physical objects, ranging from simple and compact structures and ruins to complex and large buildings and monuments, all enriched with intangible values. Such a variability of artefacts poses many challenges to their efficient and systematic documentation, which is fundamental to guarantee a sustainable strategy for cultural heritage protection (Masciotta et al, 2021). The current economic situation, exacerbated by the pandemic crisis, is causing a large gap and imbalance between the funds allocated to projects and initiatives promoting the maintenance and conservation of cultural heritage, and the funding that would be actually needed. This adverse factor is leading to pursue new approaches to compensate for the lack of financial resources invested in heritage maintenance programs. Within this context, preventive conservation strategies stand out as the most relevant and cost-efficient in the long-term. Driven by the principle "prevention pays off", these approaches entail periodic inspections and tracking routines aimed at minimizing damage and deterioration processes by addressing their underlying causes in due time, thus avoiding overpriced belated interventions. The benefits deriving from the continuity of regular condition screenings and preventive conservation actions can save up to 70% of the total maintenance costs (Matulionis and Freitag 1991), and digital tools can play a pivotal role in this regard. Modern geomatic

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technologies have indeed revolutionized monitoring and tracking procedures, bringing inestimable advantages in terms of real-time data acquisition and making possible the accurate digitization of any given object, regardless of its size, shape and exposure conditions.

Among the most widespread digital strategies used for the documentation of cultural heritage buildings is the laser scanning (Vacca et al. 2012; Nothegger et al. 2009; Kushwaha et al. 2020). This method enables the remote contactless acquisition of dense point clouds of real-world objects through a rapid data capturing process and a relatively simple post-processing work. Unlike photogrammetry, laser scanning can provide accurate and reliable results also in the absence of optimal lighting conditions (Di Filippo et al. 2018). The greatest advantage of laser scanning systems is the possibility to respond to the immediate conservation and management needs of cultural heritage buildings as point clouds can be extensively employed to extract reliable 2D/3D representations, generate as-built models for structural assessment purposes (Sánchez-Aparicio et al. 2014; Funari et al. 2021), cross check spatial and hierarchical allocation of objects in HBIM environments (Barontini et al. 2021), and define baseline information for tracking the evolution of structural problems over time (Korumaz et al. 2017; Wojtkowska et al. 2021; Costamagna et al. 2020), e.g. by comparing point cloud coordinates against reference planes and creating displacement maps. Other applications, particularly appealing for the cultural heritage tourism sector, include for instance the production of virtual tours and augmented reality (Masciotta et al. 2021; Mah et al.2019).

The afore-mentioned advantages explain why 3D laser scanning is nowadays profitably employed in many different fields for advanced terrestrial and aerial surveying (Luo et al. 2019; Lercari 2019; Mokros et al. 2021). Though, as far as built cultural heritage is concerned, the main challenge remains in the dual need for high-quality 3D digital models at an affordable cost, easily accessible and reusable (Di Giulio et al. 2017). Regarding the affordability, the progressive miniaturization and cost reduction of sensing components is contributing to the spread of more flexible and low-cost 3D scanning solutions (Nocerino et al. 2017) able to reconstruct complex and large-scale environments with a simple walk across the area of interest, without resorting to time-consuming static multiple-scan approaches (Sánchez-Aparicio et al. 2019). Interesting applications concern the mapping of underground cavities and excavations for collapse risk management (Dewez et al. 2017; Eyre et al. 2016) and the mapping of forests for inventory purposes (Mokros et al. 2021). Applications of mobile mapping systems to the documentation of cultural heritage buildings are also increasing in recent years (Zlot et al. 2014; Di Filippo et al. 2018).

Once high-quality digital replica are available, they can be efficiently employed to facilitate monitoring activities and support decision-making processes for preventive conservation only if integrated within a Geographic Information System (GIS), i.e. a geospatial database combined with software tools for storing, analysing and visualizing those data along with the great variety of additional alphanumeric information and attributes that can be associated with it (Sánchez-Aparicio et al. 2020). Through GIS, data is attached to a unique location and accordingly identified, hence previously unrelated information – once geographically referenced – can be linked to one another and filtered through GIS queries. GIS applications for heritage preservation at territorial level are already well-established and widely employed (Vacca et al. 2018; Agapiou et al. 2015; Ortiz et al. 2016). Conversely, applicative examples at the building level are still limited (Apollonio et al. 2018; Bitelli et al. 2019). In this regard, the real breakthrough shall consist in the combination of geoinformatics, web mapping and network interoperability by leveraging the latest advances in Information and Communication Technology (ICT), Internet of Things (IoT) and Virtual Reality (VR) and blending the potentialities of each technology into a unique platform for a straightforward digital-based management of cultural heritage buildings. Another issue yet to be addressed is the transfer of synthetic, yet valuable information, between the experts (technicians and inspectors) and non-expert (building owners and managers) users of such tools in order to facilitate the direct engagement of the latter in the daily condition screenings and maintenance activities of their buildings. This is indeed a key aspect for the full actuation of a preventive conservation strategy sustainable in the long-term.

Numerous research programmes, including Horizon2020, Horizon Europe, the Joint Programming Initiative on Cultural Heritage, the Interreg Sudoe Programme, or the NextGenerationEU funds, have been promoting the use of advanced digital technologies for cultural heritage preservation, and several projects are riding the wave of the digital revolution in this field (Wu & van Laar 2021). Among the most recent and successful initiatives is the European project “HeritageCare – Monitoring and preventive conservation of historic and cultural heritage” (SOE1/P5/P0258), which has developed a digital-based integrated methodology aimed at providing enhanced tools and services to document cultural heritage buildings and engage owners in the conservation process of their legacy (Masciotta et al. 2021).

The present work originates from the framework outlined above and intends to move a step forward in the field of preventive conservation of cultural heritage buildings through digital technologies. This is pursued with the implementation of an integrated digital workflow that combines different documentation and virtualization strategies in order to demonstrate how raw point clouds can be enriched with meaningful real-time data and informative 360° virtual tours, and how these enhanced virtual representations can be imported into a unique Web-GIS database designed to streamline the conservation process of built cultural heritage and guarantee to both expert and non-expert users accessibility and reusability of the stored information for future comparative analyses. The PlusCare database recently developed within

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the scope of the HeritageCare project (Masciotta et al. 2021; Sánchez-Aparicio et al. 2020) will be employed for the purpose of this work.

The remaining sections of this paper are organised as follows. Section 2 provides a critical overview of the main strategies used for the 3D documentation and virtualization of cultural heritage buildings along with their working principles. Section 3 reviews the multiple uses of the digital products obtained through these technologies in the field of preventive conservation and management of built heritage. Section 4 presents two successful case studies where the afore-mentioned digital tools have been applied and integrated to obtain value-added reference information ready to use for condition mapping and to assist facility managers in the actuation of proactive preventive actions. Finally, Section 5 summarizes the main conclusions of the work.

2. Technologies for digitization and virtualization of heritage buildings

As previously stated, the main aim of this work is to evaluate the potentialities offered by the integration of different virtualization strategies in order to enhance and streamline the management of the conservation process of cultural heritage buildings according to a preventive approach. Particularly, the following strategies are herein considered: i) LiDAR and ii) 360º photography.

2.1 LiDAR technology

LiDAR is a range-based method that allows to accurately measure and capture spatial data in nearly real-time by laser range finding. The basic working principle is the emission of a light beam (laser) that bounce off the object surface and is returned to a receiver. To calculate the sensor-target distance, laser scanning systems operate according to one of three ranging principles, i.e. Time-of-Flight, Phase Shift, or Triangulation (Historic England 2018):

- Time of Flight (ToF) or pulse scanners compute the distance to the surface based on the time elapsed between the emission of the light signal and the reception of the return signal. Such devices allow to capture data over great distances, up to 1km or more, and can reach accuracies of 2-6 mm even at longer ranges (1 mm at closer ranges), but they often feature slower acquisition rates.
- Phase Shift scanners perform the distance calculation by comparing the phases of both emitted and returned signals. These scanners offer similar accuracies as ToF systems and traditionally have higher rates of data capture, normally greater than one million points per second, while their typical operating range does not exceed 300 m.
- Triangulation-based scanners project a laser beam onto a target and exploit a camera to calculate – based on trigonometric laws – the distance of the spot or stripe of laser light onto the object. Laser triangulation scanners operate with a precision level of the order of 0.05-1 mm, but only up to distances of 2-3 m due to the limited field of view shared between the laser and the camera. Applications are therefore limited to small objects.

The sensor-target distance is also complemented by the angular measurements captured by the additional sensors of the system (i.e. servo-engines and rotational mirrors) that allow to deviate the laser beam to specific positions and to generate a discrete representation of the entire scene, i.e. the so-called point cloud. This process of digitization is known as laser scanning.

Apart from the measuring principle, laser scanning technology can be further classified in static and dynamic, depending on the portability of the device. The former encloses laser scanners that acquire data from a fixed point of view, at ground level, such as Terrestrial Laser Scanners (TLS); whereas the latter includes laser scanners that acquire data from a movable position, like i) mobile mapping systems (MMS), which are used at ground level; and ii) airborne laser scanners (ALS) that are equipped in aerial platforms such as drones or planes (Figure 1).

Depending on the complexity, size, and exposure of the cultural heritage object to digitalize, each of these scanning systems can offer more or fewer advantages over the others. To select the correct recording strategy, it is important to consider and balance various aspects, either intrinsic to the technology, such as data resolution/accuracy, acquisition rate, minimum and maximum operating range, and extrinsic to the method, like operational conditions, object scale and material surface. Table 1 compares these aspects in accordance with the type of laser scanner technology and with the characteristics of the heritage object to digitalize.

In line with what exposed in Table 1, the most feasible 3D scanning solutions for the digitization of heritage buildings are the terrestrial laser scanner and the mobile mapping solutions. Both systems are critically analysed in the following sections.

2.1.1 Terrestrial laser scanner

TLS can acquire with millimetric accuracy millions of point measurements through the generation of 3D point clouds, allowing a fast and accurate three-dimensional reconstruction of the scanned objects. By default, these point clouds contain the spatial position (in Polar or Cartesian coordinates) of each point as well as the intensity values of the returned laser beam, giving as a result a grey-scale 3D point cloud. In order to obtain a real colour point cloud of the site it is necessary to add the RGB information captured through a digital camera, either integrated into the laser scanner or external. While the integrated camera carries out the image acquisition at the same time as the laser scanner, thus featuring lower acquisition times, the external camera requires the use of panoramic roundabouts or external mounts to perform the image acquisition, thereby requiring more time but providing better results in terms of geometrical resolution and a major control of the camera parameters (i.e. ISO, exposure time and aperture). In either case, it is necessary to capture a wide set of images to cover the scanned object all around and obtain the so-called 360º imaging (see also Section 2.2).

As only surfaces visible from the actual TLS position can be captured, a multi-scan approach must be followed in case of complex and massive geometries – which are rather common in cultural heritage applications – to avoid data occlusions and achieve a reasonable coverage of the desired scene (Shanoer et al. 2018). This means that the scanner must be placed at multiple locations, or scan stations, trying to ensure a trade-off between scans with optimal incidence angle and total number of stations. Redundant scan stations can in fact lead to unnecessary error accumulations (Korumaz et al. 2017; Wojtkowska et al. 2021) as each of them is placed into a local coordinate system, making necessary to carry out an alignment phase in order to refer all the scans to a common coordinate system.

Nowadays there are plenty of methods for the alignment of points clouds. However, three are considered as the most important: i) the target-based method, ii) the plane-based alignment; and iii) the cloud-to-cloud method. The first one is based on the recognition of feature points among different scan stations, such as the centre of artificial targets (planar or spherical). The second one allows aligning different scan stations through the extraction and matching of common planes. Finally, the third one is based on the use of the so-called Iterative Closest Point (ICP), an optimization algorithm that enables to minimize the difference between the common points of two point clouds. Among the three, the target-based method is the faster one since the centre of the targets can be extracted and matched in an automatic way. Yet, this method requires at least three common targets between consecutive scans, which need to be defined while planning the scan stations. Conversely, plane-based and cloud-to-cloud methods do not require the use of targets but as regards the latter, given its local convergence, it is necessary to provide at least a rough alignment between scan stations by identifying three common points. This phase is conventionally carried out in the office. Still, the latest advances in positioning systems and computer vision approaches are now allowing to perform a pre-alignment phase in the field using Global Positioning Systems, Inertial Measurement Units, as well as feature detection and matching strategies. This way, one can obtain directly onsite a rough pre-alignment between consecutive scan stations that can be considered as a good approximation for computing the final alignment by using the ICP algorithm (Biason et al. 2019).

2.1.2 Mobile mapping systems

Progresses in sensor miniaturization, positioning systems and robotics have recently led to the development of mobile mapping systems (MMSs) as cost-efficient alternatives to traditional TLS technologies. MMSs can be considered as compound systems consisting of three main parts: i) a position and navigation unit for spatial referencing; ii) one or several sensors for mapping; iii) and a time referencing unit for data synchronization. The data provided by these parts enable to obtain fast and comprehensive digitization of heritage buildings and sites in the form of 3D point clouds (Alsadik et al. 2019). The main distinguishing feature of these systems is their capacity of acquiring data while on movement, being possible to equip them onto different mobile platforms (e.g. vehicles or boats, among others). This aspect places MMSs as the most promising digitization strategy for cultural heritage, especially when dealing with large scale and complex environments.

Presently, there exist two main groups of MMSs: i) vehicle-based MMSs; and ii) portable MMSs (PMMSs). The former group uses a direct georeferencing system (GNNS) and remote sensing integrated into a vehicle, either terrestrial or airborne. Due to its speed, this type of sensor is typically devoted to urban-scale applications and large outdoor capture projects. The latter group combines instead an inertial measurement unit (IMU) with a rotatory lightweight laser head able to capture 2D laser profiles or segments of the scene. For this type of device, the GNNS positioning system acquires less importance since they are mainly focused on mapping indoor environments. Data from both IMU and laser sensors are integrated through the simultaneous location and mapping (SLAM) algorithm. This algorithm processes the data in an incremental way: the scanner's path is tracked as the device moves and, step by step, a detailed map is built by iteratively extracting and matching geometrical features and IMU data. The SLAM algorithm can be run either in real time (online SLAM) or offline (full SLAM), being the second alternative the most accurate one, especially if the data acquisition protocol follows a closed-loop solution where start and end positions are identical.

Within the group of PMMSs, three main categories can be distinguished: i) back-pack; ii) hand-held; and iii) trolley (Figure 2). The first two options belong to the wearable mobile mapping systems (WMMSs) and are extremely versatile, whereas the trolley solution, although providing better accuracies, is less flexible than WMMSs, featuring lower mobility and hindering the operator from the possibility to map different floors without stopping the system or to scan narrow spaces. This limitation places the WMMS as the preferred solution for indoor mapping of cultural heritage buildings. Yet, their use requires a proper design of the data acquisition path, which involves – for instance – the minimization of "there and back" loops, where the path simply doubles back on itself, as well as other operational questions (Di Filippo et al. 2018).

Although the quality and precision level of WMMSs are more than sufficient in most practical applications (Di Filippo et al. 2018; Nocerino et al. 2017; Cabo et al. 2018; Lagüela et al. 2018), it must be stressed that their accuracy is not as high as conventional TLS systems, and it might result not enough for monitoring incipient structural deviations. Moreover, the data acquisition protocol plays a crucial role since it might promote a wrong convergence of the SLAM problem, leading to the appearance of non-linear deformations and/or duplicated objects. Still, the flexibility of a tool that can be easily handled to operate within difficult places and the speed at which data can be acquired over large areas do compensate for these disadvantages (Historic England 2018), being possible to reduce the total time invested for 3D digitalization of about 10 times as compared to the time required by employing static TLS solutions (Di Filippo et al. 2018). It follows that WMMS applications for 3D surveying of cultural heritage buildings are going to drastically escalate in the upcoming years, especially when seeking an accessible technology able to balance spatial accuracy, scan acquisition rate and in situ versatility.

2.2 Panoramic photography

Panoramic photography is a technique that allows capturing digital images with horizontally elongated fields of view (FoV), typically larger than 100º and in most cases greater than the human field of view, which is estimated to be about 75º (vertical FoV) by 160º (horizontal FoV). These images are commonly known as 360º photos and can be exploited for the generation of immersive virtual environments by applying specific projections (e.g. cubic, cylindrical and spherical) that enable to pass from the panoramic image to the virtual environment itself.

Since the field of view of panoramic images is larger than the field of view covered by standard digital images (i.e. 75º for the focal lens of 28 mm), additional hardware components are needed to generate images covering up to 360°. Among the different possibilities, ranging from parabolic/hyperbolic mirrors to simpler mirror balls, the most common tools are represented by multi-sensor devices and reflex cameras equipped with rectilinear or fish-eye lenses and mounted on a panoramic roundabout (Figure 3). Individual images need to be acquired from the same position to reduce the so-called parallax effect that can appear due to the presence of a non-unique nodal point during the data acquisition. In the following, both hardware components are briefly addressed.

2.2.1 Multi-sensor devices

Multi-sensor devices for panoramic photography refer to all those sensors made up of several independent cameras (lens and sensor), but sharing a common mount that allows capturing at the same time all the information required for the creation of the 360º image. Within this framework, two main groups can be distinguished: i) multi-sensors made up of two lenses and camera sensors, and ii) multi-sensors made up of several lenses and camera sensors. The former group comprises devices whose mount includes a frontal and a rear fish-eye lens, each able to capture a panoramic image with 180° coverage; these images are then registered together with an automatic post-processing stage, obtaining the final 360º image. The second group includes devices provided with several rectilinear lenses and camera sensors that are oriented over a sphere. Each sensor can capture a portion of the whole scene that is overlapped for a small part with the adjacent sensors. Once all the images are acquired, a stitching process must be carried out to solve the external and internal orientation of the cameras. Nowadays, thanks to the unceasing advances in photogrammetry and computer vision, this process can be performed automatically. It starts with the key-point extraction and matching among individual images. The extraction of key-points is carried out through the well-known Scale-Invariant Feature Transform (SIFT) algorithm, while the matching is performed using an L2-norm and the Random Sample Consensus (RANSAC) algorithm (Brown and Lowe 2007). This enables to compute the homography matrix between adjacent images. After that, a global registration phase needs to be carried out to minimize the error accumulation. During this stage, the distortion parameters of the camera, its focal length and angular positions are optimized.

Finally, the panorama is generated by projecting the images on the spherical coordinate system. Gain compensation and multi-band blending are used in order to fuse all the image properties. Although featuring a less demanding post-processing stage, this type of device shows several limitations in comparison with the ones described next, particularly: smaller sensor size, implying less light sensitivity; lower resolution of the output; presence of parallax artifacts due to the construction of the system; and lower control over the photographic parameters, such as the aperture.

2.2.2 Reflex cameras mounted on panoramic roundabouts

Reflex cameras equipped with a rectilinear or fish-eye lens can be used in the place of multi-sensor devices to obtain a high-resolution 360° coverage of the desired scene. In this case, the equipment is mounted on a panoramic roundabout that allows capturing images towards a specific direction and in a fixed position. Note that each image differs from the others in the angular position, not in the spatial one. The number and direction of each photo are determined by the characteristics of the lens, being required not only to cover the interest area but also to ensure an overlap of about 20º between adjacent images. Table 2 compares the number of images and direction required for generating a 360º image with different types of lenses. As expected, a higher number of images allows to achieve panoramic photos with higher resolution, but this necessarily implies a greater investment of time for the data acquisition and post-processing stages. The images acquired by reflex cameras are finally stitched together using the same process as multi-sensor cameras equipped with rectilinear lenses.

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3. Laser scanning and panoramic photography for preventive conservation and management of CH buildings

Laser scanning represents today one of the key technologies for the conservation of heritage buildings due to its active nature, fast data acquisition and accuracy. The main objectives of the numerous heritage-related applications found in the literature concern the acquisition of high-resolution data for the generation of as-built solid models, and the automatic or semi-automatic extraction of case-specific features for damage analysis. The first objective arises in response to the necessity to smooth the transition from half-raw survey data (point clouds) to realistic geometrical models useful for HBIM projects or advanced numerical simulations. Depending on the final product, this transition phase is known as Scan-to-BIM or Scan-to-FEM. The works carried out by Zhang et al. (2015), Barontini et al. (2021) and Angulo-Fornos & Castellano-Román (2020) belong to the first category, exploiting the 3D point clouds captured through a static multi-scan approach (TLS) to cross check quantitative spatial information and derive geometrically accurate parametric entities for HBIM purposes (Figure 4a). The recent work from Mora et al. (2021) moves in the same direction, but a mobile mapping system (WMMS) is employed instead for capturing the point cloud of the heritage structure under investigation and generating therefrom the different families of HBIM objects with great accuracy and level of detail. Many other relevant works, such as those by Conde-Carnero et al. (2017) and Angjeliu et al. (2020), fall within the second category, being devoted to the use of the terrestrial laser scanning technology for generating as-built digital replica ready to be employed for advanced numerical simulations of historical constructions (Figure 4b). Analogously, the work performed by Sánchez-Aparicio et al. (2021) resorts to the most recent wearable mobile mapping solutions to obtain - with a reduced *in situ* workload - a digital product of a historic masonry church that could be imported into a FEM software for advanced structural analysis.

The second objective pursued by literature works focusing on laser scanning products is linked to the need of making full use of the added value that high-resolution spatial data acquired via LiDAR technology can provide in the field of conservation of heritage buildings. Point clouds are indeed formed by a discrete yet very refined number of data points whose spatial interrelationship should remain unchanged over time provided that the structure does not undergo any deformation. Hence, by comparing their spatial allocation against reference planes, it is possible to exploit TLS or WMMS outputs to spot and accurately quantify tilting mechanisms and deformations (Mukupa et al. 2017). However, the current developments in feature extraction algorithms are extending the use of these methods also to the automatic or semi-automatic recognition (intensity- or spatial-based) of other damages, such as moisture, biological colonization and material loss, among others. In this regard, the pioneering works by Del Pozo et al. (2016), Sánchez-Aparicio et al. (2018) and Valero et al. (2019) are worth mentioning. In all three cases, the authors extracted damage information by using the geometrical relation between the points composing the point cloud as well as the reflectance values of the laser beam (Figure 4c).

While laser scanners remain the most recognized and used geomatics technique for conservation purposes, from past decade an increasing number of works are devoting their attention to the full exploitation of the products obtained from panoramic photography in order to obtain a complete virtualization of heritage buildings and sites. The popularization of this technique is due to the great ratio between easy-capturing/processing and to the sense of immersivity that 360° images provide (Napolitano et al. 2018; De Fino et al. 2022; Mah et al. 2019). Panoramic images are spatially located into a unique map, allowing a continuous virtual navigation across the captured environment. This product, commonly known as virtual tour, can entail much more than a mere collection of sequential pictures. Indeed, multiple information can be linked to the tour by means of interactive hotpots. This way, users can virtually navigate within the heritage building and access at the same time all the information therein embedded in the form of images, videos, URL links or even PDF files. Contents may include relevant data concerning the conservation of the heritage site, such as description of surveyed damages, historic information, condition assessment reports, and values of monitored parameters, among others. Several literature works have employed this resource for conservation proposes. For instance, Napolitano et al. (2018) resort to the panoramic photography for generating a virtual platform that can be employed as a supporting tool for the conservation of the Princeton University. In this case, the authors propose the mapping of damages onto the panoramic images as well as the use of hotspots for linking information related with them. On the same line are the works carried out by Mah et al. (2019), Sánchez-Aparicio et al. (2019), Balleti et al. (2019) and Bassier et al. (2018). In the first work, the authors exploit the 360° virtual tours to address the preservation of intangible values inherently associated with the assets located within the analysed heritage structure and with the ritual practices therein performed. To this end, they generate panoramic virtual tours enriched both with the information collected via different personal interviews as well as with historic data. On the other side, Sánchez-Aparicio et al. (2019), Balletti et al. (2019) and Bassier et al. (2018) employ 360° virtual tours as imagery inputs of a queryable documentation platform for the enhancement and preventive conservation of cultural heritage.

Lately, hybrid approaches combining laser scanning and panoramic photography with the aim of exploiting the advantages of both technologies are becoming the new trend in the conservation of historical constructions. The works of De Fino et al. (2022) and Sánchez-

Aparicio et al. (2020) have paved the way in this regard. Particularly, De Fino et al. (2022) suggest the use of the virtual tours as the basis of a web platform within which different types of information sources can be included, such as historic images, aerial photos captured by drones, supplementary reports and 3D point clouds generated from Structure-from-Motion (SfM) photogrammetry, all placed within the tour in form of hotspots (Figure 4d). The latter is included in the model by using a Web-GL technology (Potree viewer). Meanwhile, the rest of the information is rendered thanks to the use of web-programming languages such as HTML-5 or CSS-3. Conversely, Sánchez-Aparicio et al. (2020) present an extension of the conventional virtual tours (like those previously mentioned) by integrating them with a geo-spatial database which also includes real-time updates of the data acquired from multi-sensor monitoring systems as well as standardized technical sheets and condition reports automatically updated from a dedicated web-based application. Regarding the monitoring network, the work proposes the use of Key Performance Indicators to allow synthetizing the huge amount of captured data into easy-reading values. These are ultimately stored into the geo-spatial database and plotted onto the virtual tour in the form of coloured hotspots where the red indicates out-of-threshold values (potential risk of damage) and the green colour indicates values falling within the established tolerance range (no risk of damage). Thanks to the use of a geo-spatial database, the embedded information can be filtered and queried according to different criteria (e.g. out-of-tolerance inclinometers placed in the top floor, ground floor sensors detecting excessive levels of CO_2, and the like), and the platform is able to place the visualizer into the panorama and towards the direction where the filtered information is located.

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4. Application to two emblematic case studies

Aiming at exploring the potential of different 3D recording techniques and to demonstrate how their outputs can be efficiently integrated into multi-source spatial data infrastructure for cultural heritage virtual documentation and management, two emblematic case studies are herein exploited: a large Neo-Manueline church situated nearby Guimarães, Portugal, and a small Romanesque church located in Becerril del Carpio, Palencia, Spain. Based on the properties and capabilities of the employed devices, different data acquisition protocols and processing workflows were adopted. In the following, methods and tools employed for each testbed are fully described to foster an unbiased comparative evaluation between well-established digital documentation techniques and novel low-cost alternatives.

4.1 Digital documentation of São Torcato church

4.1.1 Case study description

Located in a small village in the North of Portugal, the Church of São Torcato is a Neo-Manueline construction built between the 19th and 20th centuries to house the body of the homonymous Saint, Christian martyr. From a spatial standpoint, the church is not oriented according to the traditional liturgical directions, being characterized by a Latin cross plan with the apse northward, at the end of the unique longitudinal nave, and the high choir above the main entrance in the southern extremity of the church, opening towards the nave and the altar. The apse is separated from the main part of the church by a transept that extends crosswise to the east and west (Figure 5). Both nave and transept are covered with a barrel vault, hiding the wooden roof truss above; while the crossing between longitudinal and transverse arms is covered with a dome that stands upon an octagonal tambour supported by four Roman arches. The façade, embellished by a central rose window and a balustrade gallery, is flanked by two towers of 58 m height. Side chapels, accessible only from the outside, extend parallel to the nave between transept and towers.

As the construction of the church stretched over two centuries, different materials were used to complete the structure. Particularly, the parts dating back to the first building phase, such as nave, transept, and towers, feature walls made of three-leaf granite masonry with regular units and thin mortar joints, whereas the parts recently reconstructed, i.e.the apse with the main altar, are made of reinforced concrete covered with granite veneer.

For many decades the church has been object of various in situ investigations, including visual inspections, topographic and geotechnical surveys as well as long-term structural and environmental monitoring campaigns, aiming at identifying the origin of the deep diagonal cracks crossing the façade and of the towers tilting (Sánchez-Aparicio et al. 2014; Masciotta et al. 2016). It was found that the mechanical characteristics of the soil under the towers and main façade were extremely poor, and this caused non-negligible differential settlements that progressively led the towers to lean forward with different oscillation amplitudes and, consequently, the façade to crack with an increasing average opening rate of 0.1 mm/year due to the growing tensile stresses originated from the towers tilting (Masciotta et al. 2017). With the aim of reinstating its sound condition, the church underwent an in-depth structural intervention between 2014 and 2015. The works involved: i) the installation of micro-piles to strengthen the towers foundation and eliminate the differential settlements, ii) the placement of post-stressed tie rods to restrain the towers, and iii) the injection of compatible mortar into the cracks to restore the material continuity. Major details about the structural intervention are available in (Funari et al. 2021). Before, during and after the strengthening works, the dynamic and static response of the church was monitored by means of a tethered sensing system, which allowed to keep under control the progress of the structural consolidation and to quantitatively evaluate the positive impact of the strengthening measures (Masciotta et al. 2017).

The last condition survey of the church was carried out within the scope of the HeritageCare project, four years after the intervention. Besides the presence of non-structural damages, especially in the form of biological colonization, bird infestation, water infiltration, efflorescence, and material discolouration, the survey revealed a permanent deformation of the vault supporting the choir, which was likely never fully recovered from the settlement-induced damage affecting the church prior to the structural intervention. Additional structural cracks were detected on the triumphal arch and along the weakest links of the lateral walls of the nave up to the roof level, highlighting the necessity to control their behaviour in order to exclude the presence of new unstable phenomena. Hence, with the aim of obtaining a high-resolution 3D documentation of the church for geo-referenced damage mapping and future comparative analyses, the information collected during the onsite visual inspection was complemented with a detailed laser scanning survey and a full panoramic imaging of the site, both indoor and outdoor, enabling the integration of multi-source data into a unique in-house Web-GIS tool conceived to guarantee accessibility, longevity, and reusability of the stored information over time from both expert and non-expert users (see also Section 4.3).

4.1.2 Data acquisition and processing

The 3D documentation of São Torcato church was performed using the Leica P20 ScanStation, a compact pulse terrestrial laser scanner that combines advanced Time-of-Flight range measurement with Waveform Digitising (WFD) technology. This innovative feature enables the instrument to achieve ultra-high scan speeds and deliver high-quality dense spatial data with low noise at extended range (120 m). The scanner is provided with an integrated high-resolution digital camera for simultaneous point-cloud colourization as well as with a dual-axis compensator for survey-grade tilt compensation. The accuracy varies between 3 mm at 50 m and 6 mm at 100 m. With a capture rate up to 1,000,000 points per second, this tool allowed to collect in one working day millions of range and angular measurements carrying precise volumes of spatial information about the church.

Given the geometry and size of the building, a multi-scan approach was followed to reach an occlusion-free coverage of the entire scene. Overall, 74 stations were needed to scan both the interior and exterior of the church and a network of registration targets were employed in each scanning position to facilitate the subsequent scan merging process into a unique coordinate system. Registration and geo-referencing of the point clouds were performed in Leica 3D point cloud processing software using the default workflow. The whole post-processing required the work of two technicians for 3 weeks. An ultra-high density 3D digital model made up by 3 billion points was obtained as a final product (later reduced to 17 million points). Representative images are reported in Figure 5.

In parallel, with the aim of collecting additional imagery inputs and create an enriched virtual model of the church, the as-built 360-degree camera Ricoh theta V was employed along with a smartphone to take panoramic views both inside and outside. The camera is equipped with two 180º fish-eye lenses that allow to shoot the target space in all directions at a single push of a button, without having to worry about camera settings, angle of view and tilt. About 110 minutes were necessary to capture 42 panoramas of 5376×2688-pixel resolution, meaning 2-3 minutes per panorama. The low-cost software Pano2VR® as well as the in-house plugin HeritageCare4Pano2VR (Sanchez et al. 2020) were employed to link the various panoramic scenes and convert still 360° photos into interactive immersive experiences (Figure 6).

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4.2 Digital documentation of San Pedro church

4.2.1 Case study description

Located in the municipality of Becerril del Carpio in Palencia (North of Spain), the church of San Pedro is a small rural temple dating back to the 13th century. The plan reflects the Romanesque style, being characterized by a single nave with three sections covered with a barrel vault made of tufa stone, whereas the square apse was built successively in Late-Gothic style (Figure 7). To adapt to the slope of the land on which it was erected, the orientation of the church does not follow the liturgical directions; in fact, the access doorway is located on the north-eastern wall. Attached to the apse, southwest side, is the square body of the sacristy covered with an octopartite ribbed vault. The bearing structure of the church is made of sandstone masonry, but white limestone is found in the belfry that stands out on the gable façade. Massive buttresses built against the outer walls allow to support the roof system.

In the past, the church was affected by differential settlements below the north part of the nave, suffering visible deformations and cracks along the tower, choir, and main nave. Hence, during 2007, extensive diagnostic investigations were carried out to assess the stability of the structure as well as evaluate the degradation state of the indoor assets. Due to the evident poor conditions, a profound restoration took place in 2011. The works involved exclusively the most urgent retrofitting measures: i) the enlargement of the buttresses foundations to reduce the stresses transferred to the soil; and ii) the strengthening of the extrados of the nave vaults by means of textile-reinforced mortar made of basalt fibres embedded into a lime-based matrix. Non-invasive restoration measures were also undertaken on the single assets to avoid their impairment and to preserve their tangible and intangible value. Yet, a long-term preventive conservation protocol that could effectively maintain both the structure and its indoor assets in good conditions was not designed, causing the closure of the cult.

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In 2019, the church of San Pedro was included within the policies of the HeritageCare project, thus the last condition survey dates to that year. As expected, the visual inspection revealed the absence of regular maintenance actions that resulted in the progress of typical non-structural damages, such as water infiltrations, moist areas, material detachment, broken tiles and widespread biological colonization (major plants and algae). Moreover, driven by the necessity to evaluate the long-term impact of the previous intervention and to compare the evolution of the structural condition, the information acquired during the HeritageCare onsite visual inspection was complemented with a fast yet comprehensive geo-referenced mobile mapping of the site and high-resolution panoramic images. The recording strategies used to generate the digital replica of San Pedro church, along with its virtual environment, were different from those employed for the church of São Torcato, thus requiring a different protocol for both data acquisition and processing. Notwithstanding, the final output integration process conveyed to the same dual-web GIS environment.

4.2.2 Data acquisition and processing

The digitization of San Pedro church was performed using the Zeb-Revo mobile mapping system. Powered by the LiDAR technology, this device couples a 2D rotating laser scanner head with an Inertial Measurement Unit (IMU) on a rotary engine. The data captured by both sensors is stored in a processing unit located within a small backpack. These devices are all carried by the surveyor whose movement provides the third dimension required to generate the 3D point cloud. This handheld laser scanner is provided with a default acquisition range of 0.60-30 m indoors and 0.60-15 m outdoors and can acquire up to 40,000 datapoints per second with centimetric accuracy (1-3 cm).

Once the data was captured, a 3D SLAM algorithm was used to combine the data coming from the 2D laser unit with those measured by the IMU sensor and obtain an accurate 3D point cloud of the church. As the process is based on an incremental procedure, in which each segment of the 2D laser scanner is aligned with respect to the previous one, a global registration was carried out by continuing the iterative process until the start point was reached (closed-loop solution) in order to minimize error accumulation (Sánchez-Aparicio et al. 2019). A total of 34 minutes (16 minutes for data acquisition with a simple walk plus 18 minutes of data processing) were needed to obtain the whole 3D representation of the building. The resulting point cloud consisted of 27 million points. Figure 7 illustrates some featured views of the final 3D representation. Despite the centimetric accuracy, the digital model of the church resulted very precise, especially in the bottom part, as confirmed by the comparison of reference distances taken during the field work through a TLS system. A lower level of detail is found only at the rear of the belfry due to the range limitations of the sensor.

In parallel to the 3D documentation, always with the purpose of creating an enriched virtual model of the church, seventeen 360º panoramas were produced from the stitching of different images (7 images/panorama) acquired with a digital single-lens reflex (DSLR) camera, model Canon 700D, equipped with a Sigma 8 mm F3.5 EX DG fish-eye lens. The stitching process was carried out in the open-source software Hugin®, investing a total of 9 minutes per panorama (2 min for data acquisition and 7 min for processing). Finally, the panoramic photos were linked together in a unique virtual experience by employing the same procedure and tools as for the case study of São Torcato church.

4.3 Integration of multi-source data into a unique Web-GIS platform

The effective implementation of sustainable and lasting preventive conservation approaches requires the use of robust tools able to store, integrate, georeference and manage huge amounts of data coming from multiple and heterogenous sources while ensuring their accessibility, transferability, and continuous informative character for both expert and non-expert users. To this end, the recently developed PlusCare system (Sánchez-Aparicio et al. 2020), a web platform combining the latest advances in geodatabase models, interoperability protocols and digitization strategies, was exploited to integrate all data acquired during the site digitization of São Torcato and San Pedro churches and create enriched digital models to provide owners and curators with an intuitive data-driven tool for planning preventive measures and future interventions based on the actual conservation needs of the building, according to the best proactive practices.

The afore-mentioned platform features a dual web environment, i.e. one for expert users (inspectors and technicians) and another for non-expert users (owners and managers), each including a tab menu that serves as easy navigation shortcuts to quickly move and browse between different categories of content (Figure 8). On one side the expert environment allows the upload, integration and management of multi-source data for the accurate mapping and diagnosis of existing damages, including point clouds, panoramic photos, data from monitoring systems, condition survey information, and whatsoever useful diagnostic record. On the other side, the non-expert user environment permits consulting such information in a synthetic and user-friendly way thanks to the intuitiveness of the virtual reality, upon successful authentication and authorization.

The current version of the PlusCare system implements the Potree viewer, meaning that point cloud data are partitioned and rendered according to an Octree data structure, and relevant annotations can be added in the form of texts and graphs to create informative dynamic 3D models. The surveyor only needs to upload to the system the 3D point cloud of the heritage building/site in laz format and a Potree script makes this conversion automatically. Panoramic pictures are uploaded to the same Web-GIS tool specifying the location from which they are taken. Then, once the main damages and deterioration processes affecting the investigated building and related indoor assets are identified and their degree of severity assessed according to a common rating system (Masciotta et al. 2021), this information is also inserted into the Web-GIS tool and properly georeferenced to automatically allow for its spatial localization across both point cloud data and panoramic images. Further information about causes, consequences and recommendations on possible mitigation or preventive actions can be associated with each documented damage and visually projected onto the final virtual environment in the form of interactive hotspots. Details concerning the development phases and all technical characteristics of this novel Web-GIS tool can be found in (Sánchez-Aparicio et al. 2020).

As regards the present case studies, the spatial and imagery input data collected during the site digitization was imported into the PlusCare system and integrated with the information acquired during the condition surveys, allowing to output for each church a unique virtual web-environment composed of 360° photos where the end user was given the possibility to navigate through the building, consult high-resolution geometric data via the 3D point cloud, visualize ongoing damages and deterioration processes, filter information concerning the conservation status of the church and its assets, as well as access recommendations to prioritize preventive maintenance actions (Figure 9). It is worth mentioning that each time new data was uploaded to the platform and georeferenced, new hotspots were automatically created inside the virtual tour and linked to the relevant information. Additionally, thanks to the JavaScript Object Notation (JSON) communication protocol that the PlusCare tool is provided with, if a monitoring system is installed in any of these buildings to better understand their environmental and structural behaviour, it is possible to retrieve in real-time updates of the monitored variables (e.g. temperature, relative humidity, luminosity, carbon dioxide, presence of xylophagous, crack width, inclination, etc.) and to automatically rate their acceptability/degree of risk with a three-colour grading scale defined according to pre-established control limits (Figure 10). For the sake of knowledge, this extra feature has been already successfully implemented in analogous cases both in Portugal (Masciotta et al. 2021) and Spain (Sánchez-Aparicio et al. 2020).

Thanks to the PlusCare system, the digital documentation and condition tracking of São Torcato and San Pedro churches became systematic since 2019. Yielding a detailed spatial understanding of the conservation issues of cultural heritage buildings, this tool can be directly employed by stakeholders to identify problems and damages that require immediate action and to lay the basis for future evaluation of the undertaken mitigation measures.

5. Conclusions

Laser scanning is notoriously one of the most used technologies for advanced visual inspection and accurate surveying of heritage buildings. Both static and mobile laser scanning systems have demonstrated to be effective for conservation purposes, although equipment cost and workload can vary significantly between the two. Recently, with the aim of making heritage more accessible to the society, attention has been paid to the exploitation of the products obtained from panoramic photography in order to obtain a comprehensive virtualization of heritage buildings and sites. Yet, the integrated application of laser scanning and panoramic imaging for preventive conservation of built heritage is not a common practice and should be fostered by providing standardized digital workflows and promoting appropriate geospatial data infrastructures. In the light of these considerations, the present work has analysed the most relevant heritage-related applications of laser scanning and 360° imaging – along with their digital products – and has presented two successful case studies in which the two surveying and virtualization techniques have been applied and integrated to obtain value-added reference information ready to use for condition mapping and for assisting building owners and facility managers in the actuation of proactive preventive actions. Given the diversity of the investigated buildings, different acquisition and registration protocols are followed to achieve the best digital product at the least cost. From the applicative examples the following conclusions can be drawn:

- WMMSs provide an efficient low-cost alternative for the 3D documentation of built heritage as compared to well-established and more expensive TLS solutions which demand acquisition and processing temporal windows 10 times higher, but the range limitations and centimetric accuracy of lightweight portable laser scanners might hinder the digitization of high elements and result insufficient for monitoring emerging structural deviations.
- As-built multi-sensor cameras feature a greater cost-efficiency enabling to save around 3 times the total time required for capturing and processing panoramic pictures with more sophisticated digital single-lens reflex cameras.
- Opting for more affordable and straightforward solutions does not necessarily jeopardize the outcome of the digitization process. Yet the final choice should be made according to the ultimate scope of the survey, the heritage object to digitize and the accessibility conditions of the site.
- Well-designed spatial data infrastructures are crucial to streamline the management of the conservation process of built heritage and to ensure accessibility and transferability of the products and information therein stored to both expert and non-expert users.

LINK TO THE FINAL VERSION:
https://www.tandfonline.com/doi/full/10.1080/15583058.2022.2069062

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Ackowledgements

This work was partially financed by ERDF funds through the V Sudoe Interreg program within the framework of the HeritageCare project (Ref. SOE1/P5/P0258), and by FCT/MCTES through national funds (PIDDAC) under the R&D Unit Institute for Sustainability and Innovation in Structural Engineering (ISISE), under reference UIDB / 04029/2020.

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a) www.faro.com b) www.geoscan.aero

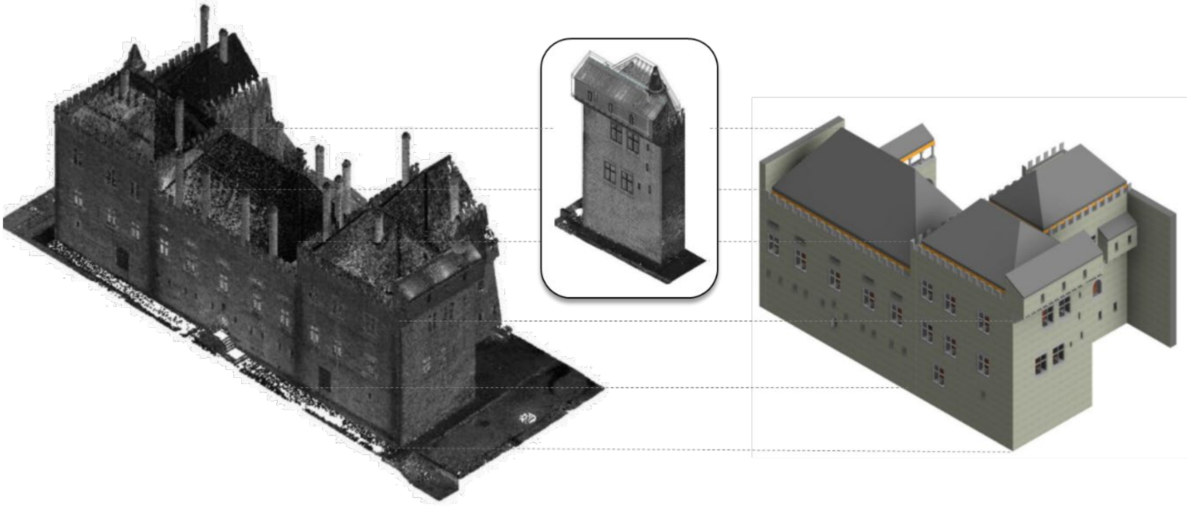
Figure 1. Examples of laser scanning systems: (a) terrestrial and (b) aerial.

a) www.leica-geosystems.com b) www.geoslam.com c) www.applanix.com

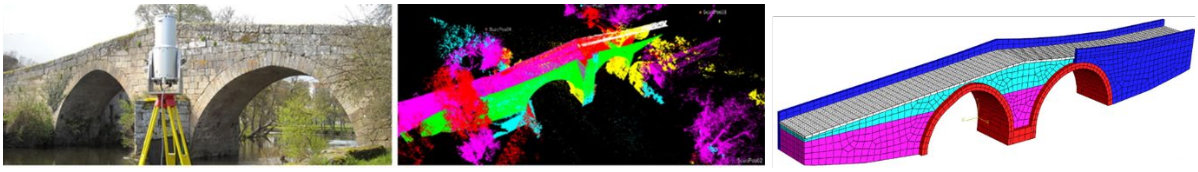
Figure 2. Examples of portable mobile mapping systems: (a) backpack; (b) handheld; and (c) trolley.

a) www.theta360.com b) www.canon.it

Figure 3. Examples of panoramic photography systems: (a) multi-sensor device with two eyefish lenses and camera sensors; (b) reflex camera with eyefish lenses.

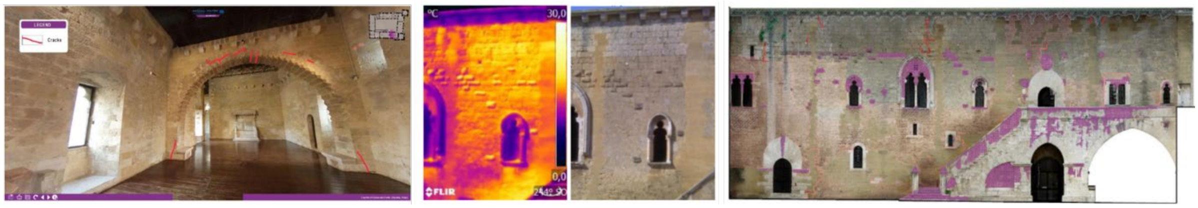


a) Transition from point cloud data to HBIM model (Barontini et al. 2021)



b) Transition from point cloud data to FEM model (Conde-Carnero et al. 2017)

c) Automatic damage recognition from point cloud data (Sánchez-Aparicio et al. 2018)



d) Panoramic scenes and ortophotos modified for damage mapping (De Fino et al. 2022)

Figure 4. Exploitation of laser scanner products and panoramic photography products for preventive conservation and management of built heritage.

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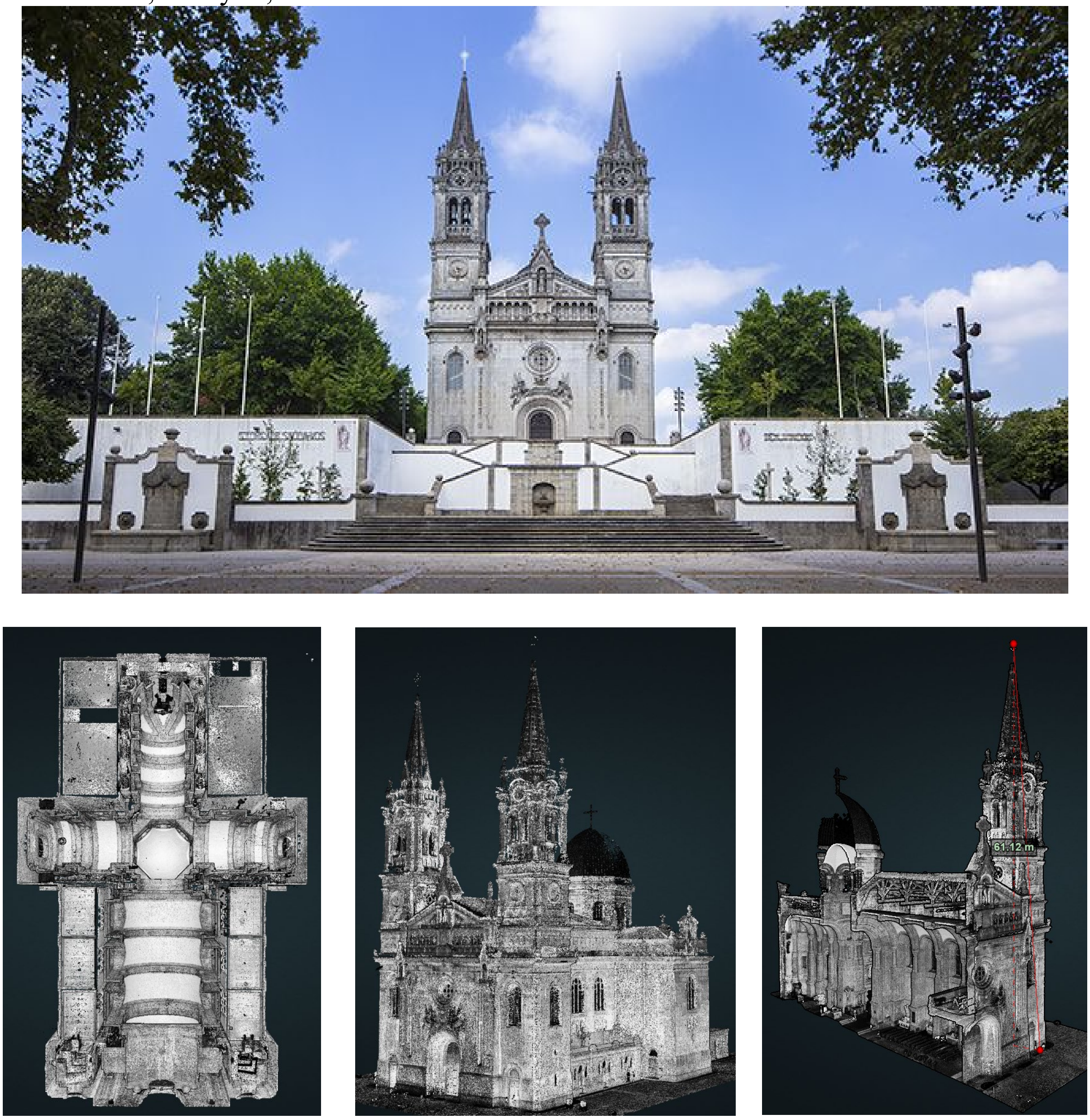

Figure 5. Church of São Torcato: exterior view (top) and representative perspectives from the final point cloud (bottom).

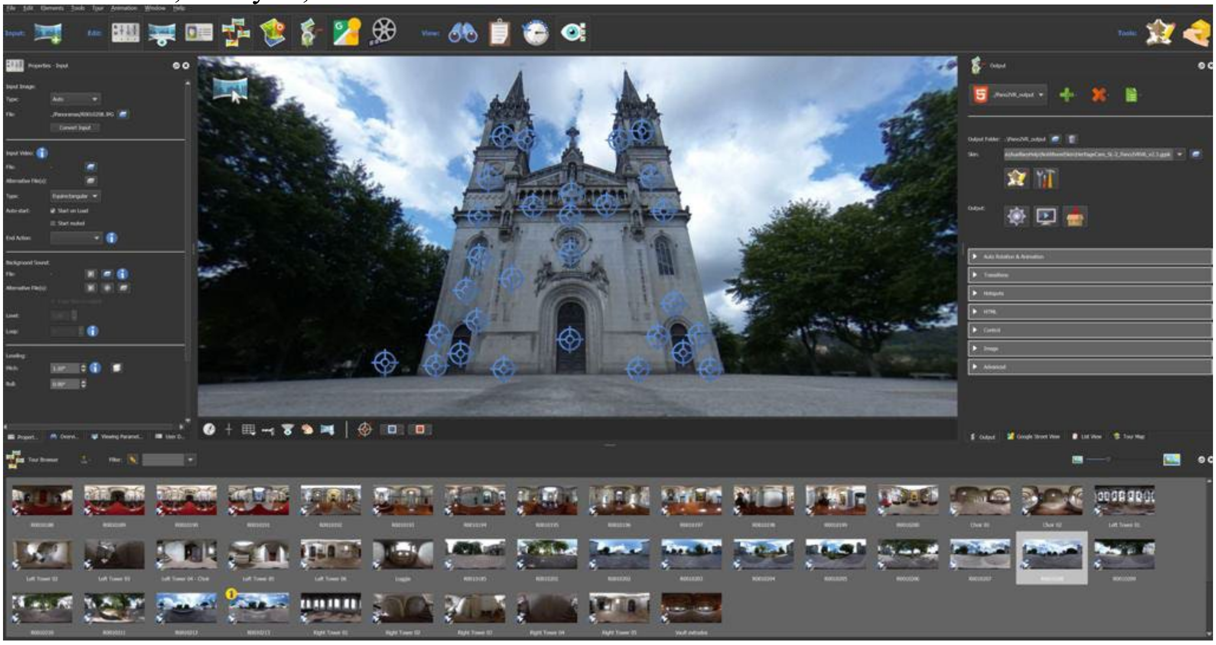

Figure 6. Creation of São Torcato virtual tour through HeritageCare4Pano2VR.

Figure 7. Church of San Pedro: exterior views (top) and representative perspective from the final point cloud (bottom).

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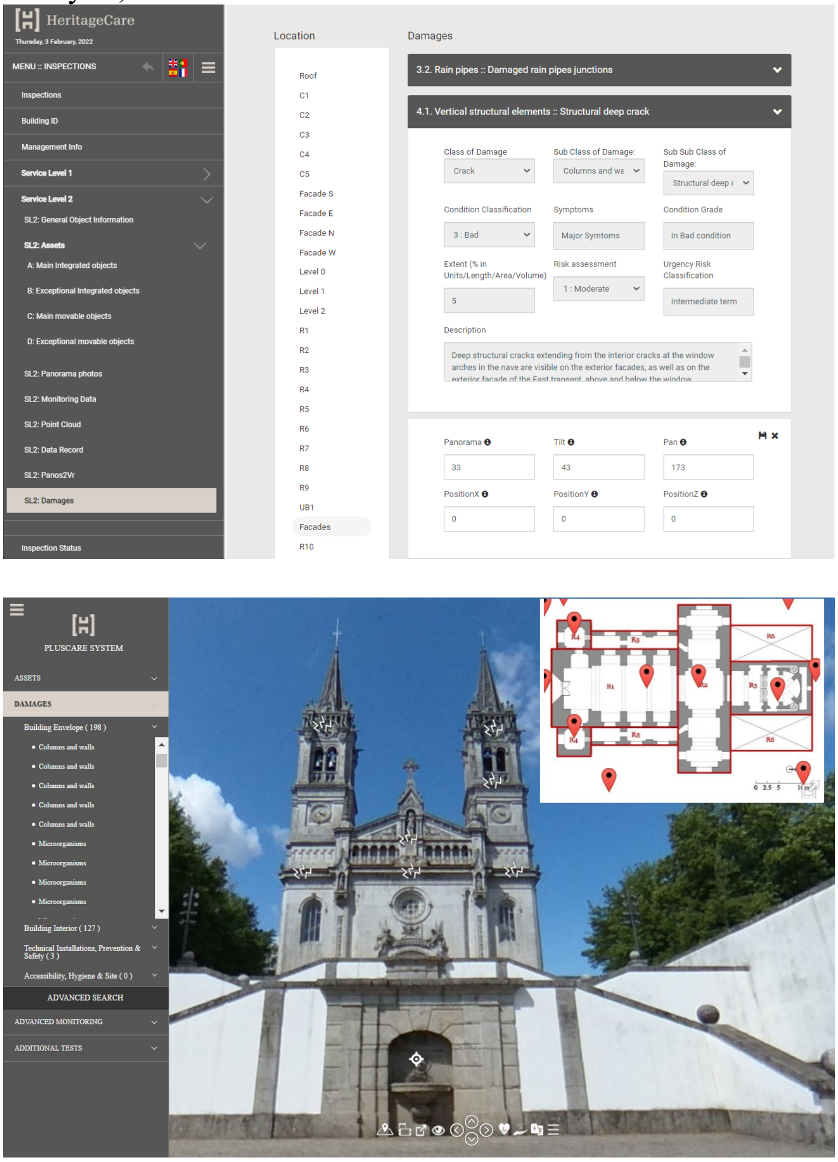

3.2. Rain pipes :: Damaged rain pipes junctions

4.1. Vertical structural elements :: Structural deep crack

Class of Damage: Crack
Sub Class of Damage: Columns and wa
Sub Sub Class of Damage: Structural deep (
Condition Classification: 3 : Bad
Symptoms: Major Symtoms
Condition Grade: In Bad condition
Extent (% in Units/Length/Area/Volume): 5
Risk assessment: 1 : Moderate
Urgency Risk Classification: Intermediate term
Description: Deep structural cracks extending from the interior cracks at the window arches in the nave are visible on the exterior facades, as well as on the exterior facade of the East transept, above and below the window

Panorama: 33
Tilt: 43
Pan: 173
PositionX: 0
PositionY: 0
PositionZ: 0

Figure 8. Dual environment of the PlusCare Web-GIS tool: expert user interface (top) versus non-expert user interface (bottom).

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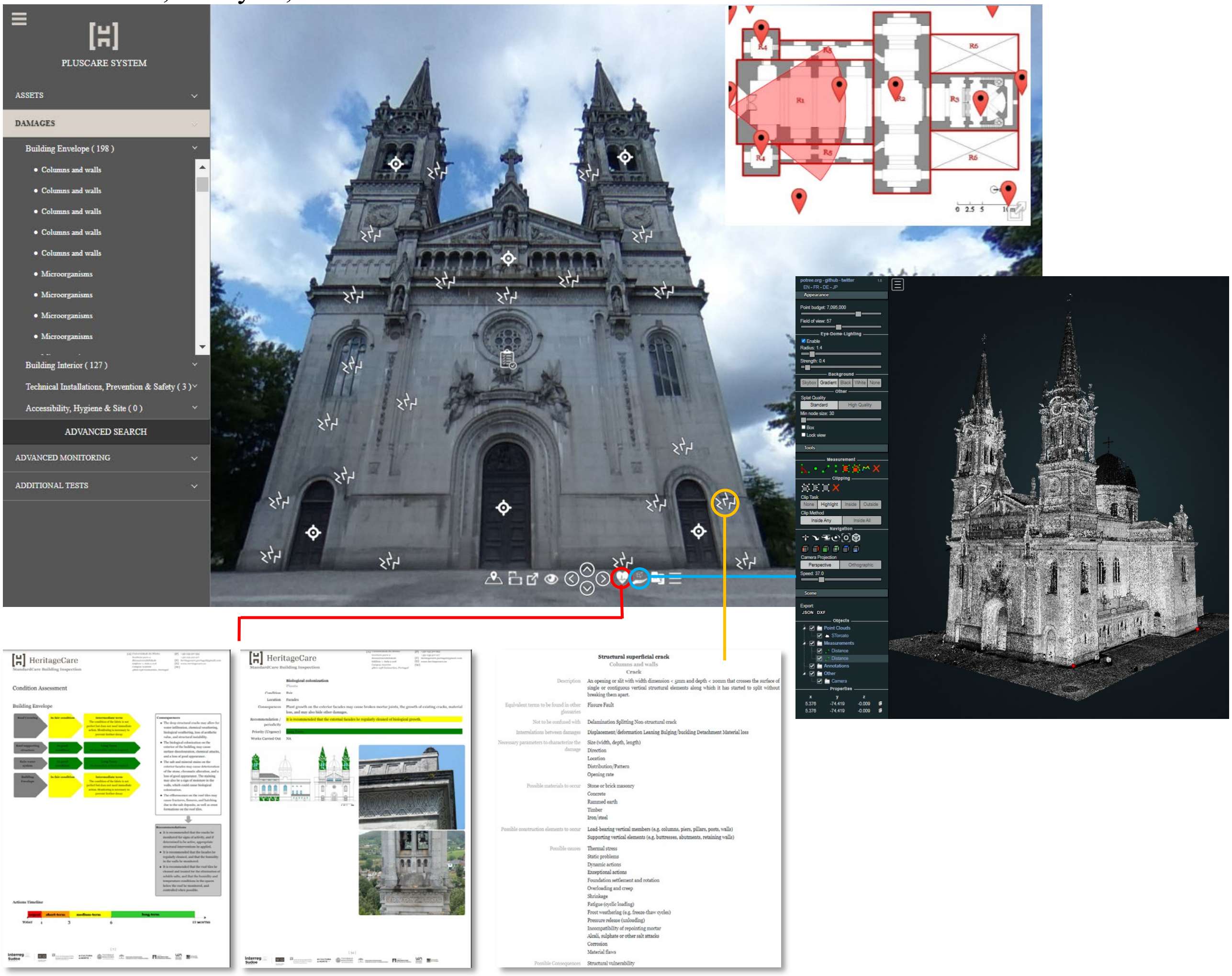

Figure 9. Integration of multi-source data (panos, laser scanning, condition assessment report, damage location and description) into the PlusCare web-GIS platform.

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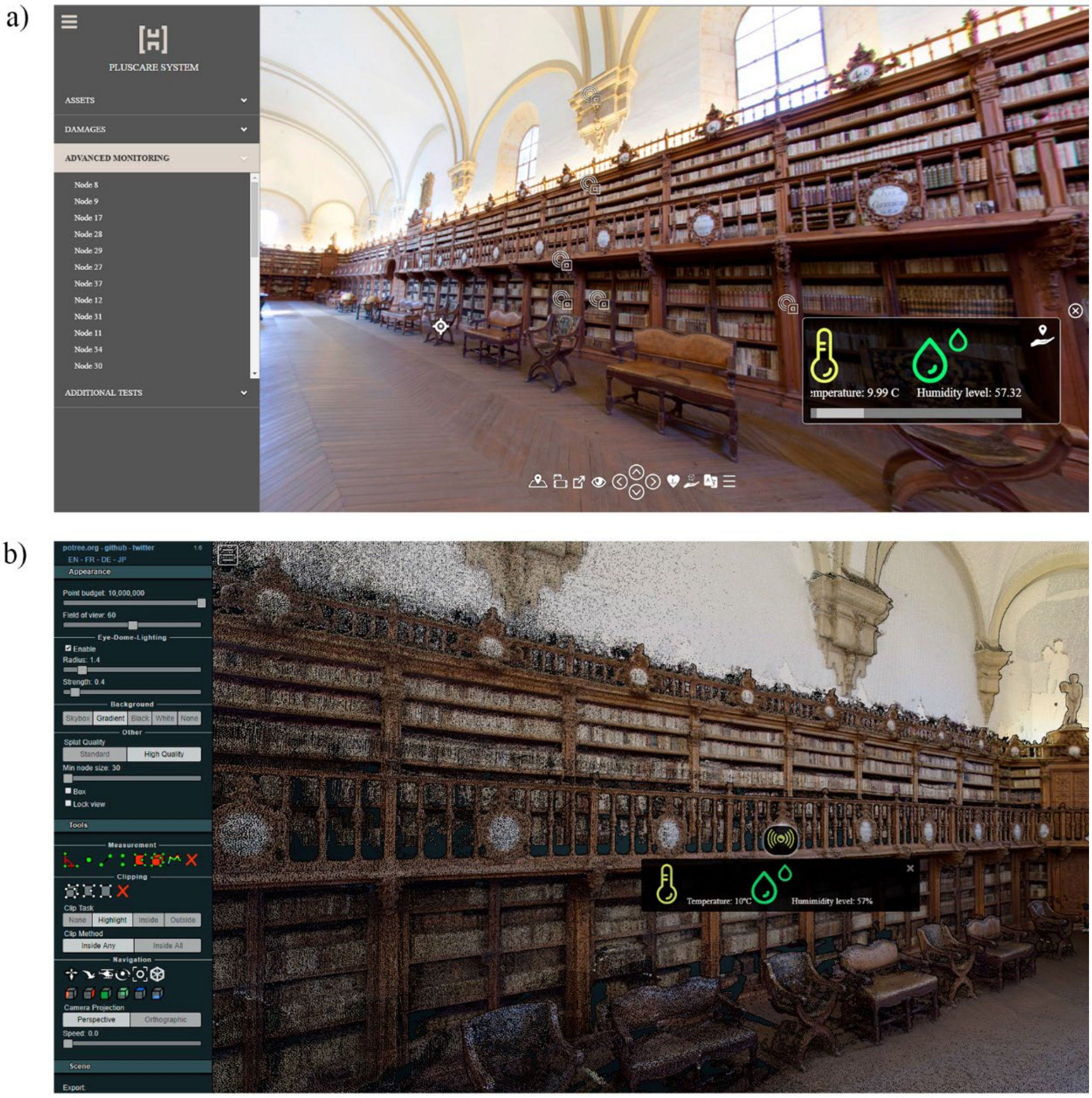

Figure 10. Example of real-time updates of monitored parameters through the Web-GIS platform: a) visualization onto the virtual tour; b) visualization onto the 3D point cloud (Sánchez-Aparicio et al., 2020).

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Table 1. Classification of 3D recording strategies for heritage digitization.

Method	**Cultural Heritage objects**							
	Large heritage areas	**Buildings**			**Movable assets**		**Underwater heritage**	**Underground heritage**
		Outdoor	Indoor		Large-medium scale assets	Small-scale assets		
			Spacious areas	Narrow areas				
Phase-shift laser scanner (SLC)	••	•••	•••	••	••	•	••*	••
Time of flight laser scanner (SLC)	••	•••	•••	••	••	•	••*	••
Triangulation laser scanner (SLC)	••	•••	•••	‡	‡	•••	••	‡
Vehicle-based (MMS)	•••	••	‡	‡	‡	‡	‡	‡
Portable MMS	••	•••	••	•••	•	•	‡	•••
Airborne laser scanner	•••	•••	‡	‡	‡	‡	‡	‡

Scoring meaning: ••• *Highly recommended* •• *Can be used* ••* *Can be used, but requires the extraction of the piece* • *Not recommended ‡ cannot be used.* SLC refers to static laser scanner and MMS refers to mobile mapping system.

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Table 1. Comparison of different lenses equipped in a digital camera with a sensor of 15,7 x 23,5 mm (1.5x crop factor)

Type of lens	Focal length (mm)	Field of view (HxV)	Number of images	Protocol description
Rectilinear lens	18	66º x 47º	24	12 images at 30º over the horizontal line (one each 30º) and 12 at 30º under the horizontal line
Circular fish-eye lens	15	180 º x 180 º	3	One image per 120º degrees in horizontal
Full frame fish-eye lens	10.5	120º (180º in diagonal)	7	One image per 60º degrees in horizontal and 1 image at 90º in nadiral position