'AUGMENTED DIAGNOSTICS' FOR THE ARCHITECTURAL HERITAGE

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ABSTRACT

Techniques and methods for assessment and control of the historical-architectural heritage have recently gained high levels of maturity in the scientific debate and professional practice. Nevertheless, they still address challenging research topics. Particularly, future developments might come from the multi-disciplinary integration of hardware and software tools, mainly used in different fields and/or with different purposes, as well as from the multi-level correlation of data by different documentary, analytical and experimental sources.

Within this framework, this article presents the methodological approaches and preliminary results of a research project: 'Contactless diagnostics for augmented reality of the cultural heritage with low accessibility', currently carried out under the funding programme of the Italian Ministry of Education, University and Research 'MIUR Start-Up'. In detail, the article provides an overview of the general goals of the project, which is focused on the development of procedures and devices for the assessment of technical and constructional characteristics in historic buildings by photogrammetric/thermographic ultralight sensors on unmanned aerial vehicles (UAVs), towards the collection and management of diagnostic data in virtual and augmented reality environments.

Thus, specific focus will be paid to the preliminary studies on a representative pilot case, where several research phases have been developed, including analysis of historic records, photographical survey for three-dimensional modelling, mapping of materials, construction techniques and decay patterns, as well as on-site investigation by non-destructive diagnostic methods. All the results will be discussed in order to address the implementation of the 'augmented diagnostics' of the monument, in terms of correlation of themes and integration of specialisms, as outlined in the introduction.

Keywords: architectural heritage, augmented virtual reality, diagnostic techniques, UAVs.

1 INTRODUCTION

Techniques and methods for assessment and control of the historical-architectural heritage have recently gained high levels of maturity in the scientific debate and professional practice. Nevertheless, they still address challenging research topics. Among them, the perspectives towards the multi-disciplinary integration of hardware and software tools, mainly used in different fields and/or with different purposes, seem to be very interesting. Particularly, the attention is focused herein on two complementary fields meeting the above-mentioned perspectives: on the one hand, the acquisition of data for survey and analysis by means of sensors on unmanned aerial vehicles (UAVs) and, on the other hand, the integrated restitution of those data within immersive digital environments based on augmented reality (AR) and virtual reality (VR).

The review of the state of the art on the topics has showed a significant number of studies and experimentations at national and international levels.

In detail, the UAV-based remote sensing, initially targeted on military purposes, has lately concerned the environment and landscape engineering, in order to provide with investigation and control especially for critical situations, as well as the geotechnical and civil engineering, for emergency management, photogrammetric survey and monitoring of visible decay patterns [1, 2, 3].

In the field of cultural heritage, the main experiences have been developed for the archaeological assets, whereas light and compact devices enable the acquisition of high-resolution

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images for accurate three-dimensional (3D) reconstructions supporting documentation and investigation of morpho-typological and material-constructional characteristics [4, 5, 6, 7, 8, 9].

Furthermore, for the archaeological heritage, and particularly for those sites with composite architectural structures, the 3D reconstructions, based on the photogrammetric survey by drones, have been exploited for the creation of AR and VR environments. In the case of AR, the purpose is generally touristic/educational. It concerns the enrichment of the perceptive experience in the real site with informative contents by models showing lost parts of the original configuration or changed parts during restoration works [10, 11, 12]. In the case of VR, the immersive digital environments make visible some areas that are not directly accessible by the visitors or enable the systematic collection and management of information on evolution phases and current state for the archaeologists [13, 14, 15].

The development of digital models for specialized technical applications also features the more limited experiences in the fields of construction and architecture. Here, immersive augmented and virtual environments have been created based on the drawings of new structures, in order to assess the spatial and functional compatibility with the existing surroundings and to support building information modelling (BIM) platforms during the building process and the facility management [16, 17, 18, 19].

All the above-mentioned researches, here briefly reported, are a valuable reference for the architectural heritage. In fact, the described approaches might be usefully applied in the process of conservation and refurbishment of historic buildings because they meet some of its key requirements. In detail, during the 'on-site' acquisition by aerial vehicles, they ensure low interference with the structural stability and operation functionality and high accessibility to areas not directly investigable. Moreover, during the 'on-desk' restitution, they guarantee comprehensive fruition of the current state, systematic implementation of all the collected data and assessment of compatibility of restoration solutions within digital platforms.

Nonetheless, beyond the need for documentation and visualization of archaeological assets and for project management of new constructions, the process of conservation and refurbishment adds the peculiarities of the diagnosis phase, where the residual technological-environmental performances and the physical-functional pathologies should be assessed, in order to address suitable interventions. Such a phase, which is strongly focused on the critical understanding of the historic fabric, might benefit, in the authors' opinion, by the described techniques and tools. Particularly, surveys by drones and AR/VR models should support the acquisition and interpretation of in situ diagnostic measurements and tests, in order to enable the reliable diagnosis of building characteristics and obsolescence phenomena.

In the light of the above-mentioned aspects, the article refers to the concept of 'augmented diagnostics', namely the integration in real and virtual building models of a framework of information that might help the operators throughout the diagnostic phases. The structured collection of data, from the on-site inspection, the consultation of historic records and the detection of relevant parameters by diagnostic techniques, should address the highly desirable and challenging multi-level correlation of different documentary, analytical and experimental sources.

2 METHODS AND TOOLS

In the light of the above-mentioned issues, the authors have recently carried out several studies and applications, in order to integrate in the 'traditional' process of architectural, technical, constructional and performance assessment of historic buildings some 'innovative' investigation systems and procedures, namely the employment of UAVs for the systematic collection of diagnostic data in AR and VR environments.

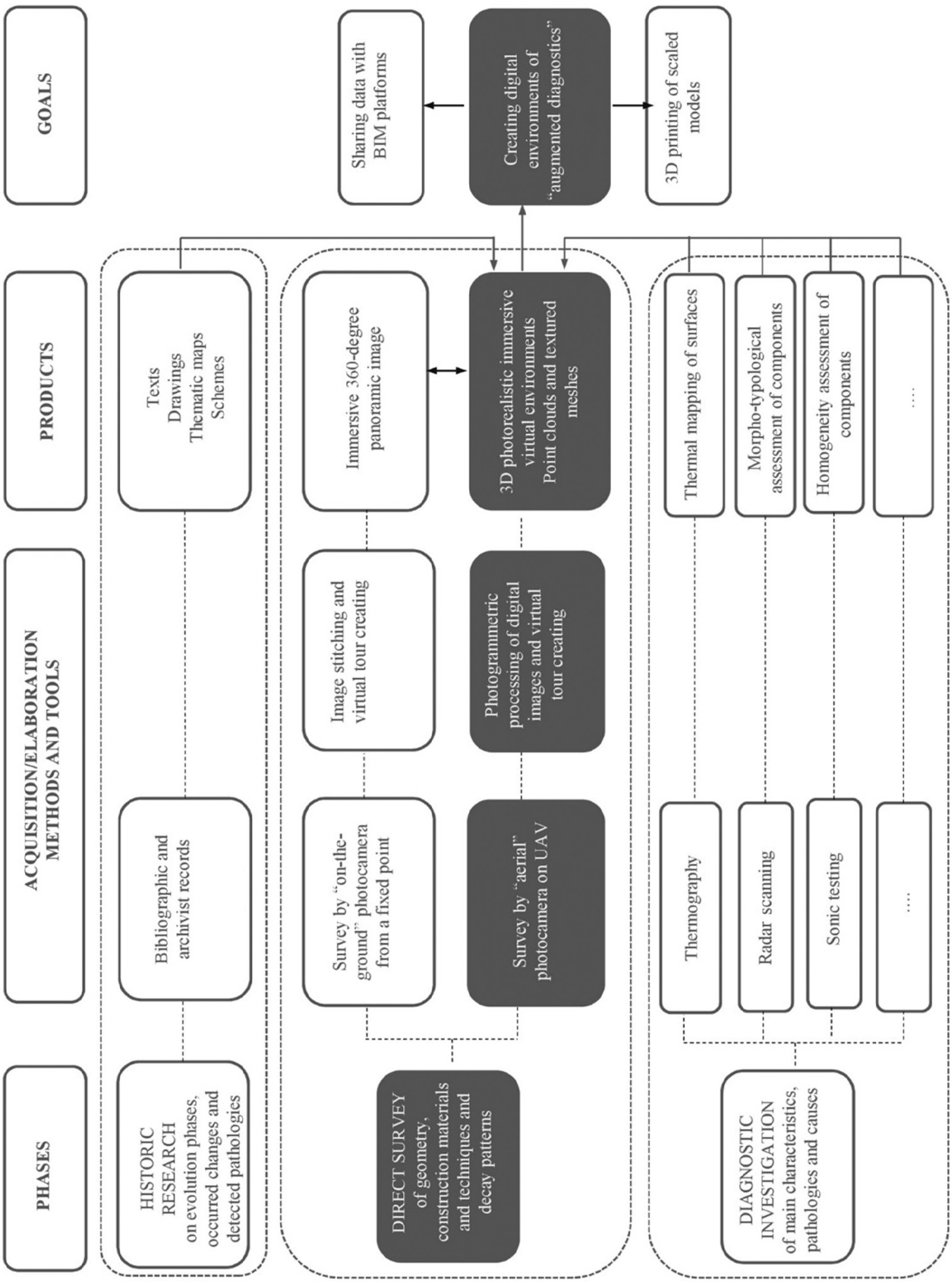

Figure 1: Methodology.

Particularly, the research project ‘Contactless diagnostics for augmented reality of the cultural heritage with low accessibility’, currently carried out under the funding programme of the Italian Ministry of Education, University and Research ‘MIUR Start-Up’ (partners: Polytechnic of Bari, University of Naples, Polishape 3D srl and B.Re.D. srl), aims at developing and validating the following key aspects:

- Definition of methodological guidelines and operation protocols for acquisition and elaboration of diagnostic information by photographic and thermographic sensors on drones, in terms of identification of technical specifications of the equipment, experimental set-ups and correlation methods with complementary data from historic research, geometry survey, mapping of construction materials and techniques, detection of decay and alterations
- Development of multi-sensorial integrated devices for aerial survey on drones that might guarantee safety, reliability and flexibility of remote control
- Creation of digital diagnosis contents and environments by AR and VR models for collection, consultation and implementation of all the results of the investigation and assessment process as decision-making tools for the operators.

Within the research, the present work describes phases and preliminary results mainly concerning the third topic, by application and validation of a general protocol (Fig. 1) on a representative pilot case, the ‘Masseria Don Cataldo’ in Adelfia, Province of Bari (Apulia Region, South Italy).

Particularly, it follows the well-established phases of the assessment process, from the historic research on the architectural evolution through the direct survey of the building characteristics and decay patterns until the on-site diagnostic investigation, towards reliable diagnosis and compatible intervention. Within these phases, it explores the potentialities of UAV-based surveys in order to develop 3D photorealistic immersive environments, as well as 3D point clouds and polygonal meshes. Such environments, also integrated with different digital models, such as 360° panoramic images from ‘fixed’ points, are proposed as ‘augmented diagnostic’ tools that enhance the virtual inspection of spaces and surfaces by a set of documental, analytical and experimental contents, such as texts, drawings, schemes, maps and measurements. The tools aim at supporting the ‘expert users’ throughout the diagnostic process. Moreover, they are potentially linkable through data interchangeability with complementary hardware and software solutions for project development and management, such as BIM platforms and 3D printing.

3 CASE STUDY

3.1 Historic Evolution and Architectural Profile

The ‘Masseria Don Cataldo’, about 30 km far from Bari, the main town of the Apulia Region, South Italy, was built through different phases.

The early structure dates back to the 17th century and it corresponds to the current ground floor. It mainly hosted storage rooms for the agricultural activities in the surrounding fields. In the 18th century, the upper floor was added to transform the rural building into a noble palace as holiday resort for the owners, the Marquises of Canneto. This construction phase is the most interesting from the architectural point of view, since it involved the addition of the monumental helicoidal entrance staircase, the round towers, the corner loggias and the stone-tiled courtyard (Fig. 2).

Figure 2: South façade of the building.

The building was further improved in the 19th century, particularly by decorative ornaments, including the outstanding main hall at the first floor, with temperas on the vault and the walls and stucco cornices, tympanums and medals across the openings (Fig. 3). For the sake of shortness, the article will focus on this hall, which is highly illustrative of the overall investigated aspects.

Furthermore, as far as the construction materials and techniques are concerned, the building shows masonry walls with outer leaves of regular limestone blocks and inner cavity filled with mixtures of mortar and stone fragments. The vaults are made out of 'tuff' blocks, which is a soft and mouldable local limestone. The stone surfaces are covered by plaster in the interiors and exposed on the façades.

Figure 3: Details of the decorations on the vault and the openings in the main hall.

Finally, as far as the state of conservation is concerned, the building, which has been abandoned for almost a century, shows general surface alteration, with plaster detachment and decay. Particularly, in order to address the discussion in the following sections, it is worth underline that all the vaults at the first floor show diffuse humidity patterns for water infiltration from the roof, resulting in several cracks at the intrados. In some cases, the cracks also develop along the walls, especially across the openings.

3.2 Photographic Survey and 3D Modelling

According to the methodology, as described in Section 2, based on the historic research and within the direct investigation, an extended campaign of photographic survey was carried out in the building towards the development of immersive digital environments.

As previously stated, the photographic survey was based on the employment of a UAV, namely DJI Inspire T600 drone, equipped with X3 FC350 12.76 resolution megapixel camera. In the main hall, the images were acquired by moving the camera along the perimeter. Six flight sessions were completed, corresponding to two heights (2 and 4 m) and three inclinations on the horizontal plane (–90°, –45°, 0°). The images were integrated with some pictures by GoPro 8 megapixel resolution camera, mounted on a telescopic pole, placed at 4 m from the floor and oriented at +90° on the horizontal plane. Such an integration was needed because the camera above the drone would frame the braces of the vehicle if oriented upwards. The software Agisoft Photoscan, which enabled the 3D photorealistic reconstruction as well as the point cloud modelling of the hall (Figs. 4–5), processed all the pictures.

Similarly, some representative rooms at the first floor were surveyed by images from a fixed point by Canon EOS M3 24.2 megapixel resolution camera, mounted on a panoramic head Manfrotto SKU 303SPH. In the main hall, the images were acquired by 360° rotation of the camera around the vertical axis with twelve 30° intervals and by 180° rotation around the horizontal axis with three 60° intervals. In this case, the software PTGui Pro was used for stitching the pictures and creating 360° panoramic images (Fig. 6).

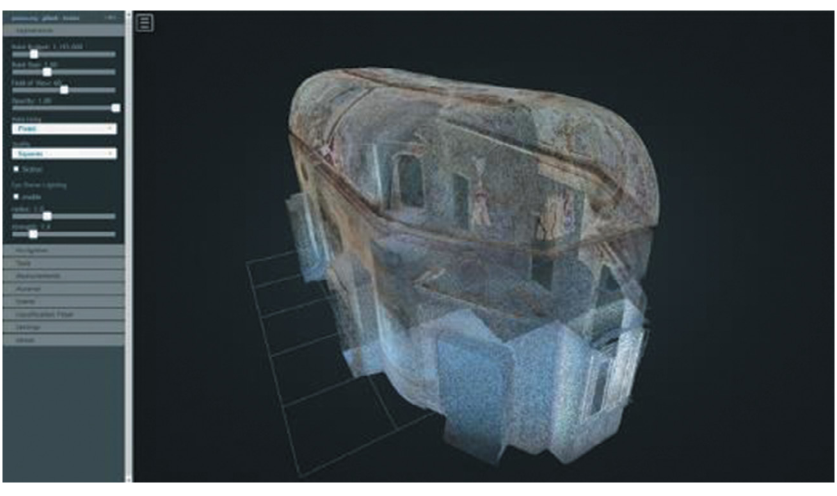

Figure 4: Point cloud of the main hall – medium density appearance (point budget 1,115,000 and point size 2).

Figure 5: Detail of the point cloud of the main hall – high density appearance (point budget 5,000,000 and point size 2).

Figure 6: A 360° panoramic picture of the main hall.

3.3 Diagnostic Investigation

The diagnostic investigation on the building mainly concerned the rooms at the first floor. In the case of the main hall, it involved the thermography of all the surfaces showing infiltration humidity and plaster detachment and the sonic testing of the walls with cracks developing from the intrados of the vault.

The thermography, performed by FLIT T430sc thermocamera, enabled the accurate identification of the extent and magnitude of the humidity patterns, as well as the detection of the masonry layout under the temperas, in order to assess the presence of cracks along the mortar joints, rather than on the stone blocks (Fig. 7). The sonic testing, performed by CMS-V3H equipment, measured the travel velocity of low-frequency mechanical waves through the vertical components, as indicator of the potential presence of incoherent cavities and decayed mortars for water infiltration that would result in the visible cracks (Table 1).

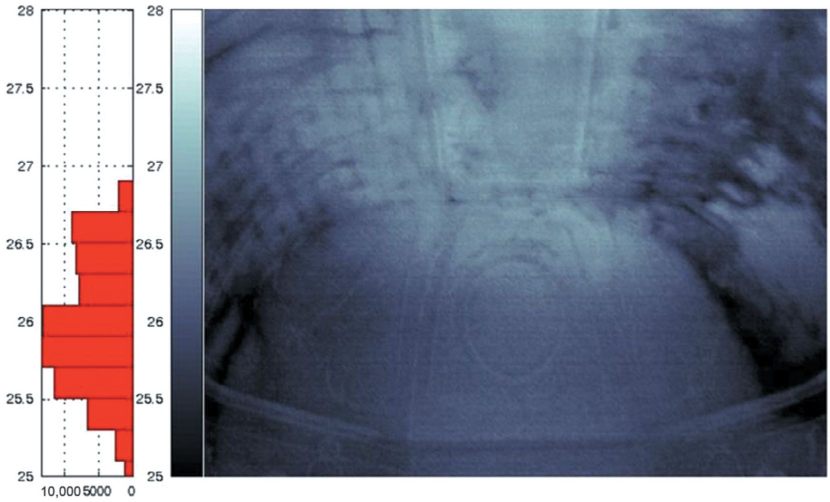

Figure 7: Illustrative thermogram of the vault.

Table 1: Illustrative set of sonic measurements of the walls.

	Measurement points	Average velocity (m/s)
	1	1436.6
	2	2130.5
	3	2354.4
	4	1665.8
	5	1815.6
	6	2278.9
	7	1715.8
	8	2016.6
	9	2546.5

3.4 Diagnostic Environments by AR and VR

All the informative contents supporting the assessment of the building, as described in the previous sections, were further processed in view of their integration.

In detail, the software Agisoft Photoscan modelled the polygonal meshes from the point clouds, as basis to extract bidimensional drawings, namely plans, elevations and sections. Furthermore, the software PTGui was used for stitching some thermograms, in order to have wider areas in the infrared spectrum, while a Matlab routine was developed and applied to interpolate the average sonic velocities and visualize them as false colour maps of the investigated areas.

Then, as previously stated, all the digital products were integrated towards their structured collection and interconnected consultation.

Particularly, the point clouds by Agisoft Photoscan were exported in the Smart City 3D platform for navigation and exploration, with functions for direct measurement of metric parameters (lines, areas, etc.) and links to external contents by ‘hot spots’ (Fig. 8). Such

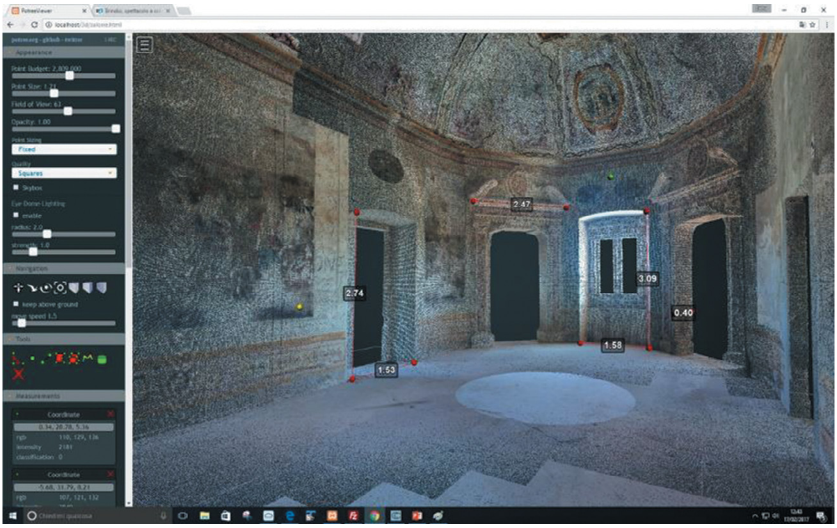

Figure 8: 'Augmented' point cloud with measurement tools and 'hot spots' to external data.

contents were arranged in brief transcripts of historical records, inventories of elements with artistic-architectural value, checklists of construction materials and techniques, maps of surface decay patterns, as well as drawings, eventually extracted from the above-mentioned polygonal meshes.

Finally, concerning the diagnostic data from on-site measurements and tests, the point clouds were linked with some 360° panoramas within virtual tour by the software Easypano Tourweaver. The immersive panoramas were conceived as 'thematic chambers', where high-resolution pictures and testing results are accessible. In the case of the main hall, the virtual tours were referred to the panoramas 'augmented' by thermal maps from stitched thermograms (Fig. 9) and sonic maps (Fig. 10), both on the corresponding visible areas.

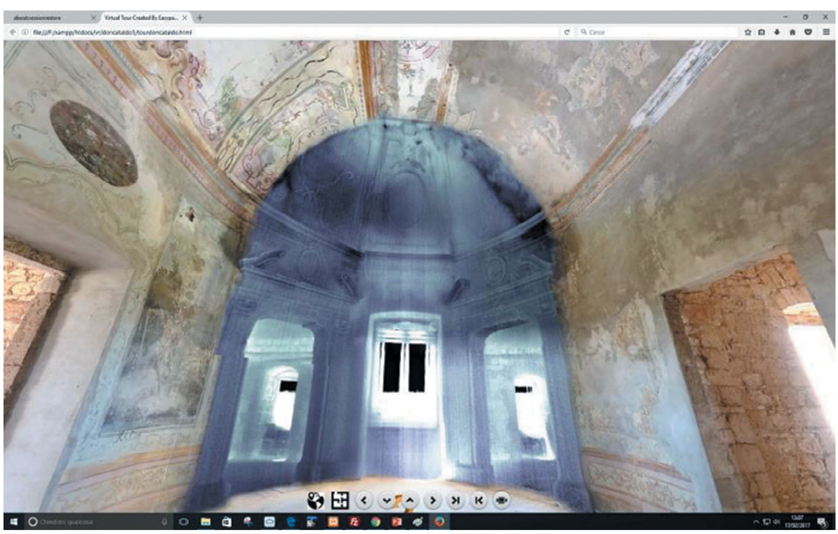

Figure 9: 'Augmented' virtual tour with thermal map.

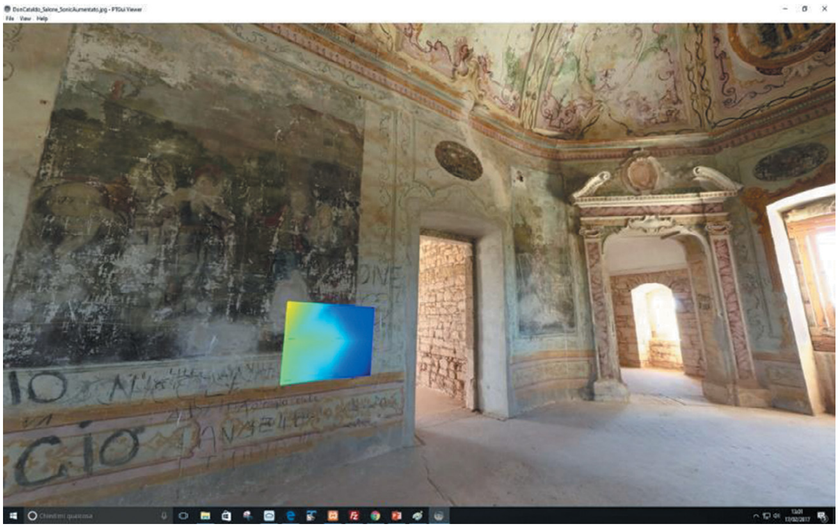

Figure 10: ‘Augmented’ virtual tour with sonic map.

It is worth to underline that the integrated analysis of all the available data usefully supported the diagnosis of the state of conservation. For instance, in the main hall, the possibility to view the infrared response of a wide area even overlapped with the visible surface, helped understand that the cracks mainly follow the mortar joints and they are much more concentrated where the humidity content is higher. Consequently, it is reasonable to consider that the over-load from the wet layers above the vault has caused a static failure of the masonry structure in the weakest points, namely the joints that easily undergo decay under seepage. Similarly, it is quite likely that the inhomogeneity of the sonic response of the walls was due to small voids and cracks in the inner cavity, again for decay of the mortar when the water infiltrated.

4 DISCUSSION OF RESULTS

The application of the protocol for collection, consultation and implementation of data resulting from the investigation and assessment of the historic building, herein briefly outlined, allows the development of some general comments on limits and potentialities of the described techniques and tools.

First, the photographic survey of historic buildings by drones is particularly attractive, because it makes visible areas that are not directly accessible, without installation of expensive and bulky scaffoldings. This aspect, which is evident for the outdoor survey of façades and roofs, is quite relevant for the indoor spaces as well, since the historic buildings are typically very high, with several jetting (cornices, jambs, lintels, sills, etc.) and recessed (niches, alcoves, etc.) elements. Nevertheless, it should be observed that the quality of the images by drones is related to the technical specifications of the camera, which should guarantee a good balance between accuracy and precision, on the one hand, and lightness and compactness, on the other hand. Similarly, the possibility to have an extra-camera above the drone to get upward pictures without visible interference of the equipment is certainly useful and feasible, on condition that the increased payload would not require large unmanageable vehicles for indoor survey.

Furthermore, the integration of the photographic survey with panoramic images at high resolution from a fixed point appears as a valuable tool to increase the data quantity and quality, especially for critical and/or interesting situations. The panoramic images are also helpful in the restitution process, in terms of faster and lighter navigation of the virtual tours compared with the point clouds, which, despite their peculiar support for assessment of geometry and morphology, might involve great computational capacity and response time.

Moreover, the correlation of diagnostic information might support the critical understanding of the relationships among building characteristics, pathologies and causes. Particularly, the creation of hot spots from the point clouds to 360° panoramic images as thematic chambers, eventually connected by rooms and/or by technique, seems to be very promising. Nonetheless, the possibility to convert the numeric value from the diagnostic test into a false colour to texture the point cloud would be very much useful, particularly whenever the diagnostic measurement refers to the third dimension, e.g. the thickness of the construction component such as in the case of georadar scanning, reconstruction of stratigraphy by videoendoscopy and sonic tomography.

Finally, the joint analysis of the surfaces in the infrared and visible spectra for wide areas might improve the reliable interpretation of the thermal response, compared with the case of limited and decontextualized portions due to short distance and/or short view factor of the thermocamera. However, the stitching of the thermograms is still critical. In fact, the apparent temperature, as measured by the equipment, is affected by the camera angle and position that might change the thermal reflection from the surroundings. Consequently, a single point might show different apparent temperatures and, thus, different false colours in two thermograms acquired with two different sensor-target relative positions. For this reason, the thermal stitching has been herein developed case by case and it still requires more detailed study to achieve robust and consistent procedures.

5 CONCLUSIONS

The research shows that the employment of drones for photographic survey and development of digital immersive AR/VR environments are highly interesting for the assessment and control of the architectural heritage, particularly when supporting the 'augmented diagnostics', namely the integration and correlation of documentary, analytical and experimental information towards the reliable diagnosis and the compatible intervention. Moreover, the validation of procedures and tools on a representative case study has proved beyond some critical issues from the operational-technical point of view, the methodological relevance and resourcefulness, in terms of low intrusiveness and high versatility of acquisition and systematic collection and management in the elaboration and interpretation of diagnostic data. Finally, it is worth to highlight that, among several open questions, great advantages would be guaranteed by the data interchangeability among AR/VR platforms and further systems, e.g. BIM and 3D point cloud processing, towards the improved flexibility and attractiveness for all the professional stakeholders.

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