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REMOTE DIAGNOSIS AND CONTROL OF HERITAGE ARCHITECTURE BY PHOTOREALISTIC DIGITAL ENVIRONMENTS AND MODELS

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Abstract

The paper will discuss a methodological workflow which is focused on the role of photoscanning-based immersive environments and three-dimensional models as tools for sharing, interpreting and elaborating diagnostic data for the assessment and control of the state of conservation of architectural heritage. Specifically, from the identification of certain fields and aims, where the available tools and functionalities meet the support needs by the stakeholders, some experimental applications are developed with reference to two main aspects. The former concerns the creation of virtual tours of panoramic scenes, which are enriched by data from preliminary investigation, in order to enable the coordinated and integrated fruition of the pre-diagnosis qualification outcome. The latter relates to the use of image treatment routines on coloured point clouds in order to carry out semi-automatic operations of decay monitoring for post-diagnosis control.

Keywords

Built heritage, assessment and diagnosis, immersive digital environments, 3D point clouds, image treatment.

1. *Introduction*

The development of photoscanning-based immersive environments and three-dimensional models, particularly coloured point clouds and texturized meshes, has recently achieved great relevance and maturity.

In particular, several studies and applications are reported in the field of the geometrical surveying of archaeological and architectural sites for the restitution of complex shapes, surfaces and spaces, supporting both specialised studies (Guidi, Russo, & Angheleddu, 2014; Koutsoudis, Vidmar, Ioannakis, Arnaoutoglou, Pavlidis & Chamzas 2014; Campanaro, Landeschi, Dell'Unto, & Leander Touati, 2016) and educational dissemination (Pierdicca, Frontoni, Malinverni, Colosi, & Orazi, 2016); Balsa-Barreiro & Fritsch, 2018; Katz & Tokovinine, 2017; Girgenti, 2018).

On the other hand, the field of virtual photorealistic reconstructions for the qualification, assessment and control of building characteristics and pathologies seems less developed. In fact, the scientific literature in this area is very recent and constantly evolving. It mainly concerns:

- The development of digital platforms for the management of photorealistic environments and models, which are enriched by geo-referenced and semantically structured information for the correlated interpretation of thematic maps and diagnostic data (Soler, Melero, & Luzón, 2017; Messaoudi, Véron, Halin, & De Luca, 2018; Napolitano, Scherer, & Glisic, 2018; Mandelli, Achille, Tommasi, & Fassi, 2017; Barreau, Gaugne, Gouranton, Point, & Manipulation, 2017; Kuroczyński, Hauck & Dworak 2016; Nespeca & De Luca, 2016);
- The elaboration of coloured point clouds, which represent onsite experimental measurements as false colour maps within 3D models (Agrafiotis, Lampropoulos, Georgopoulos, & Moropoulou, 2017);
- The implementation of image treatment procedures for the automated detection of materials, construction techniques and decay patterns (Hallermann, Morgenthal, & Rodehorst, 2015; Sánchez & Quirós, 2017; Mohan & Poobal, 2017; Valença, Dias-da-costa, Júlio, Araújo, & Costa, 2013; Prati, Rrapaj, & Mochi, 2018).

2. *State of the Art*

A critical review of the scientific literature allows for the identification of some key issues, which address the development of the methodological workflow in section 3.

Firstly, it should be observed that a great variety of solutions is available for the representation of the built heritage – from photogrammetry to laser scanner surveying, and from digital mapping to building information modelling – as well as for the management of these representations, extending from digital models to immersive environments, from virtual tours to informative systems that integrate and correlate digital contents, and from on-site augmented reality applications to the simulation of virtual dimensions enriched by sensorial interaction. The selection of the most suitable solutions depends largely on the specific context.

In general, given that augmented and interactive dimensions are mainly the target of touristic experiences, scholars in the field of architectural studies outline the potential of photoscanning-based panoramic scenes and three-dimensional models, which are to be explored through virtual tours and managed by platforms for their connections to external contents and the creation of thematic layers and attributes. The above-mentioned tools are generally preferred to alternative systems. For instance, the acquisition by 3D laser scanners is considered too expensive and challenging in the case of inaccessible areas, which can be easily surveyed by drones that are equipped with photo cameras. Similarly, restitution with the help of CAD-based HBIM models might be difficult and ineffective in representing realistically irregular shapes and decorated surfaces, especially if the available graphic documents are missing or lacking.

In particular, among the most interesting and inspiring experiences, it is worth mentioning some information systems such as the following:

- NUBES, an open source web platform for describing, analysing, assessing, documenting and sharing heterogeneous data within point clouds, by several functions, including the insertion of geo-referenced links to archive files and annotations (lines, points, polygons) on the surfaces as representations of specific characteristics (cracks, alterations, and so on) (De Luca, Busayarat, Stefani, & Veron, 2017);
- MONDIS, a web and mobile application for enriching photo-realistic three-dimensional models with information on damage patterns, in order to address decision-making support procedures for the selection of compatible treatments (Cacciotti et al., 2013);
- MONUMENTUM, an environment for the numerical modelling of the built heritage for the structural assessment (De Luca et al., 2013);
- AIOLI, a collaborative platform for the storage of different types of documents (video, texts, images, audios, and so on) by cloud technology, and direct annotation of 3D models of graphic information, which are also arranged by time scales (De Luca et al., 2017).

It should be underlined that all the above-mentioned experiences are based on specific ontologies that enable the taxonomic classification of the building system and sub-systems, in terms of materials, construction techniques and architectural characteristics, in order to achieve a cross-evaluation of the dependencies among semantic attributes/investigation factors.

A further key issue which emerges from the literature review concerns some prerogatives of the specialists in the assessment and diagnosis of the architectural heritage. In fact, on the one hand, specialists require the systematization, communication and correlation of an extraordinary variety of documentary, analytical, experimental records that are very heterogeneous in terms of their typologies and themes. On the other hand, they aim at the transversal assessment of this data in order to update “preliminary knowledge” to a state of “consolidated knowledge”. These two aspects, although complementary, require quite different tools and functionalities: the former especially needs data storage and arrangement, while the latter especially needs data analysis and elaboration, with a subsequent impact on the related methodological-operational complexity, as well as on the required employment of time and cost resources. Consequently, several intuitive and immediate applications are available to implement informative models and virtual tours for 360° panoramas, where on-market software products, such as Kolor Pano-tour Pro © or Easypano Tourweaver ©, might be customized according to the user’s purposes of representation, classification and localization of multi-media contents, in order to enable easy fruition and management. On the other hand, some complex and robust platforms have been developed and tested for multi-faceted objects and detailed observations, where accurate restitutions, in the shape of high-resolution coloured point clouds, might be exploited for the extraction of metrical data and/or optical properties.

In light of the above-mentioned issues, the role of photoscanning-based immersive environments and three-dimensional models for the assessment and control of the state of conservation of architectural heritage should be outlined, taking into account the application contexts and goals. In particular, the type, sophistication and reliability of the applicable tools and functionalities should be strictly targeted at the complexity of the building, the nature, extent and magnitude of the decay, as well as the available logistical-operational resources within the wider concept of compatibility that governs the refurbishment and restoration of historic structures.

Consequently, starting from a critical review of the literature and ongoing research by the authors (De Fino, Scioti, Rubino, Pierucci, & Fatiguso, 2018; De Fino, Scioti, Rubino, & Fatiguso, 2017; Galantucci & Fatiguso, 2018), this paper will discuss a methodological workflow, based on the identification of processes, fields and aims, where photoscanning-based immersive environments and three-dimensional models might support data sharing, interpretation and elaboration for the assessment, diagnosis and control of the architectural heritage (section 3).

As a next step, within the general context, a case study is presented of Palazzo Palmieri in Monopoli, Puglia as validation of the proposed procedures and technologies (section 4). In this case study some experimental applications are developed in detail with reference to two main aspects. The former concerns the creation of virtual tours of panoramic scenes, which are enriched by data from preliminary investigation, in order to enable the coordinated and integrated fruition of the pre-diagnosis qualification outcome (section 4.1). The latter relates to the use of image treatment routines on coloured point clouds in order to carry out semi-automatic operations of decay monitoring for post-diagnosis control (section 4.2).

3. Methodological workflow

Based on the insights reported in sections 1 and 2, a methodological workflow is here proposed (Fig.1) which outlines the role of photoscanning-based environments and models for the investigation, analysis and monitoring of the state of conservation of the built heritage. It is worth underlining that the workflow does not neglect the relevance of HBIM tools, as discussed by the authors elsewhere (Bruno, De Fino, & Fatiguso, 2018), even if those tools seem to be more appropriate for the following phases of design and management of the conservation/restoration/maintenance project.

This workflow is based on the preliminary identification of the application aims (A), which are in turn related to tools (T) and functions (F).

Specifically, whenever the purpose concerns the investigation and restitution of building characteristics and pathologies (A1.1), as well as the archiving and sharing of geo-referenced analytical, documentary and experimental records (A1.2) at the preliminary knowledge stage, the acquisition of 360° spherical pictures of interior rooms and exterior areas is recommended by high-resolution photo cameras on panoramic heads (T1.1). In this case, the most required functionalities are the navigation of virtual tours of panoramic scenes (F1.1), which are enriched by hotspots to external contents with read-only files, such as historic datasheets, checklists, videos, maps and diagnostic reports (F1.2), and to thematic panoramas with decay mapping related to cracks, dampness, and surface alterations (F1.3).

Such a photorealistic environment should enable speedy, intuitive and comprehensive restitution and fruition of the site conditions, as well as systematic arrangement of heterogeneous and various information, with their positive impact noted on the communication and correlation among different domains and specialists, which are typically involved in the process.

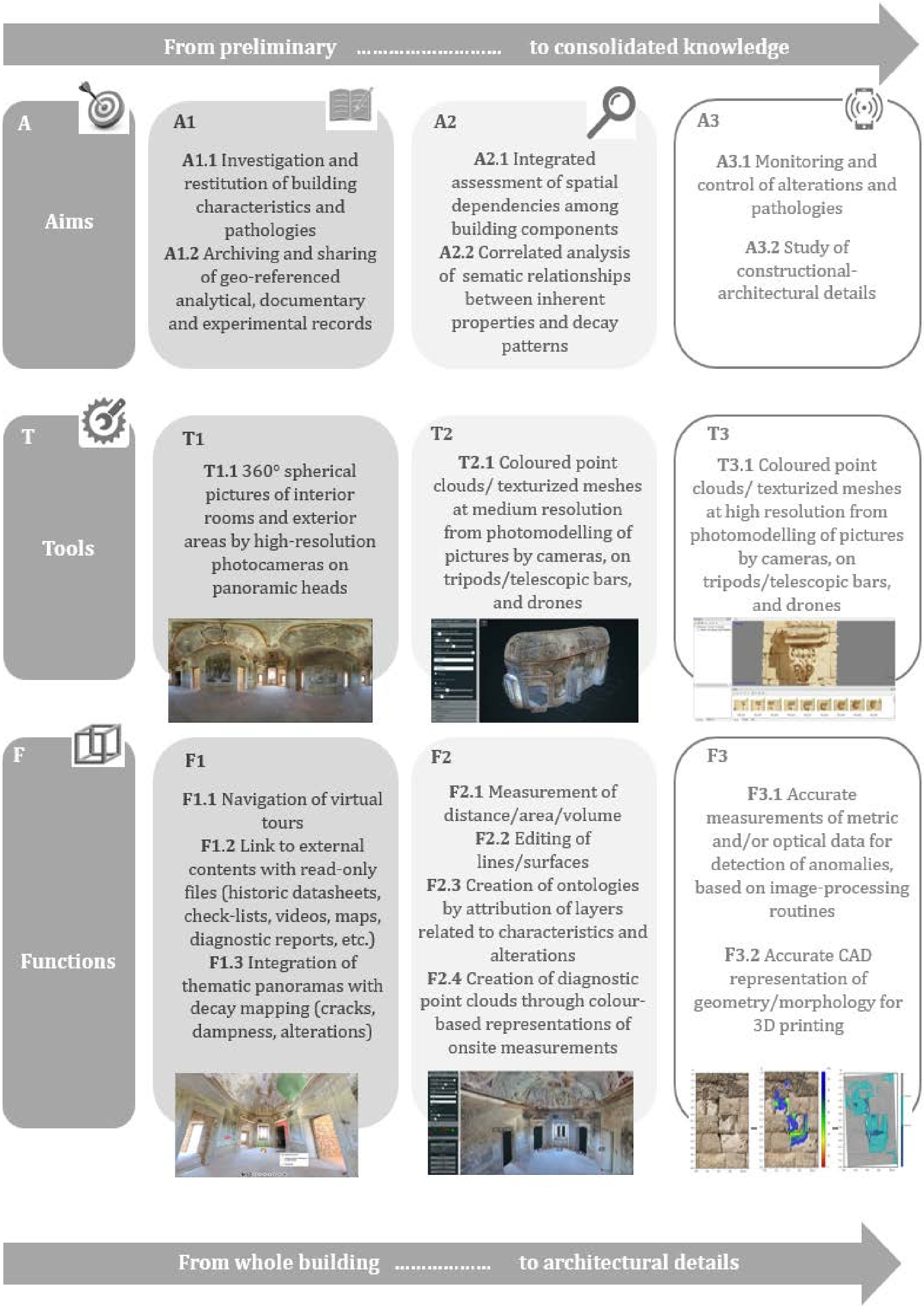
In this way, virtual tours are meant to represent a general and essential diagnosis framework for the whole building, because they might enable the cross-assessment of multi-level and multi-discipline investigation data.

According to this approach, photorealistic 3D models should include a following stage for increasingly detailed analyses on limited parts, as specific and optional contents to be accessed and interrogated from the virtual tours, in order to upgrade the preliminary knowledge into consolidated knowledge, whenever further observations or elaborations are required.

For this purpose, coloured point clouds and texturized meshes, from the photo-modelling of pictures by cameras, on tripods/telescopic bars, and taken from drones (T2-T3), might be added to the above-mentioned read-only files for critical understanding of the historic fabric, based on indirect (A2) or direct (A3) interrogation.

The indirect interrogation treats two aspects.

The first aspect concerns the assessment of spatial and morphological dependencies among building elements (A2.1), in order to identify the origins and causes of potential pathologies. For instance, both structural and humidity problems might be diagnosed only by a wide-ranging



A1

A1.1 Investigation and restitution of building characteristics and pathologies
A1.2 Archiving and sharing of geo-referenced analytical, documentary and experimental records

A2

A2.1 Integrated assessment of spatial dependencies among building components
A2.2 Correlated analysis of sematic relationships between inherent properties and decay patterns

A3

A3.1 Monitoring and control of alterations and pathologies

A3.2 Study of constructional-architectural details

T1

T1.1 360° spherical pictures of interior rooms and exterior areas by high-resolution photocameras on panoramic heads

T2

T2.1 Coloured point clouds/ texturized meshes at medium resolution from photomodelling of pictures by cameras, on tripods/telescopic bars, and drones

T3

T3.1 Coloured point clouds/ texturized meshes at high resolution from photomodelling of pictures by cameras, on tripods/telescopic bars, and drones

F1

F1.1 Navigation of virtual tours
F1.2 Link to external contents with read-only files (historic datasheets, check-lists, videos, maps, diagnostic reports, etc.)
F1.3 Integration of thematic panoramas with decay mapping (cracks, dampness, alterations)

F2

F2.1 Measurement of distance/area/volume
F2.2 Editing of lines/surfaces
F2.3 Creation of ontologies by attribution of layers related to characteristics and alterations
F2.4 Creation of diagnostic point clouds through colour-based representations of onsite measurements

F3

F3.1 Accurate measurements of metric and/or optical data for detection of anomalies, based on image-processing routines

F3.2 Accurate CAD representation of geometry/morphology for 3D printing

Fig. 1: Methodological framework

overview, both in plan and elevation, of the shape, extent and distribution of the visible damage and alteration patterns. The second aspect is related to the creation of ontologies that semantically relate the building attributes (material, construction technique, trend of environmental and structural parameters, etc.) with the decay patterns towards the cause/effect assessment (A2.2). For instance, the diagnosis of stone deterioration requires the cross-analysis of intrinsic agents – presented in the form of a typology of support, installation procedures, and mechanical-chemical-physical characteristics – and extrinsic agents, such as exposure, microclimate. For both these aspects, the main desirable functions concern, among other things, the measurement of distance/area/volume (F2.1), the editing of lines/surfaces (F2.2), and the creation of ontologies by the attribution to point/lines/areas of thematic layers to the taxonomy of characteristics, alterations and measurements (F2.3).

On the other hand, direct interrogation is related to the extraction of metric and/or optical data for diagnostic purposes. This might be the case for the medium-long term monitoring of cracks and surface alterations (A3.1), which are subject to accurate measurements and semi-structured assessment of physical anomalies and/or colour variations, based on image-processing routines (F3.1). Alternatively, it might concern the employment of reverse engineering techniques by 3D printing (F3.2), starting from a very detailed survey and restitution of the geometry/morphology (A3.2).

According to this vision, photorealistic 3D reconstructions for spatial and semantic analyses might be featured in medium resolution (T2), which in turn guarantees acceptable elaboration and interrogation speed, taking into account that they are “relationship” tools rather than “representation” models. On the other hand, if the reconstructions are meant to enable direct observations, they should be highly accurate (T3), which comes at naturally greater computational costs, even if for much more limited building portions.

Finally, it is worth stressing that the described methodological structure, where comprehensive virtual tours of panoramic scenes are connected to focused three-dimensional models, is based on a scalar approach. In fact, the proposed procedures involve increasing complexity and provide an improved accuracy, while the extent of the application areas gradually decreases, in order to guarantee the above-mentioned desirable compatibility between the complexity of involved issues and the sophistication of employed tools.

4. *Case study*

In order to validate the workflow, which was presented in section 3, the proposed methods and tools are next applied to a representative case study, the noble Palmieri Palace, which is located in the historic centre of Monopoli, in the province of Bari, Puglia. This example of monumental architecture was built in the second half of the XVIII century from a pre-existing building. It was used for two centuries as the residence of the noble family Palmieri. After this, it hosted several public functions: from 1907, it was a male orphanage at the upper floor; from 1921, it was a centre of arts and handcrafts, when the building was donated to the Congregation of Charity; from 1965 until 1990 it was an art institute. Then, since the 1990s, the Palace has not been used, except for some occasional cultural events. Throughout the XX century, when the functional use became public, a series of restoration works is documented that has aimed to eliminate several structural problems. Among them, it is relevant here to mention the replacement of some stone blocks of the pillars in the courtyard, in order to reinforce them against the occurring buckling due to high loads, decay of materials, and the slenderness of the elements. Similarly, the replacement with cement-based mixtures of the poor filling materials in the inner core of the cavity masonry walls was carried out to consolidate the structural systems. Nowadays, the Palace is organized on four floors, except for a side volume of two floors. The entrance, through a monumental portal on the main façade, leads into an internal courtyard, which most of the rooms are arranged around. The basement is made out of calcarenitic stone, while the elevation is constructed out of softer local tuff. In the case of the first three floors, the rooms are covered with masonry vaults of different typologies – barrel, groin and cloister. They are structural elements in most cases. However, on the second floor, corresponding to the noble apartment, they are mostly lightweight false ceilings supported by the wooden floors above. On the other hand, on the fourth floor, the rooms are covered by iron/bricks or concrete/bricks slabs. From an architectural point of view the main façade stands out for its bossage, the rich decorative elements around the openings, and the upper cornice, while temperas and ornamental wallpapers feature throughout the noble floor.

4.1 Virtual environments for preliminary knowledge systematization

The application of the workflow to the case study has firstly concerned the systematic arrangement of all the information gathered throughout the pre-diagnosis activities, including historical research, onsite inspection, survey of construction materials and techniques, mapping of decay, and non-destructive investigation (A1). For these purposes, the whole building was made remotely accessible via the creation of a virtual tour – by the software Easypano Tourweaver © - of 360° scenes – by panoramic camera Samsung Gear 360 C200 (T1). Specifically, the camera, which uses two fisheye lenses with 15-megapixel sensors on either side of the device, is able to capture a 360° scene by stitching together two simultaneous 180° views with automated colour calibration and exposure mode. Thus, the recurring acquisition scheme has been set as follows: for the indoor spaces, one station for each room, with the camera at the centre; for the outdoor areas, a station each 15m in plan and each 3m in height, keeping 5m as wall distance.

It is worth mentioning here that such an acquisition procedure is very speedy, simple and intuitive. In fact, it shortens the onsite survey procedures. In the case of the case study, five floors, including the roof level and about one-hundred rooms, were acquired and processed in two working days by two operators. Moreover, this results in the reliable documentation of the state of the whole building at a certain time for a subsequent remote assessment. Finally, it creates a common base, which all the different specialists involved in the restoration/ refurbishment/ maintenance process might refer to for sharing their thematic contribution.

Furthermore, in order to exploit the virtual tour, not only to display the environments for the restitution and fruition of the site conditions, but also as a tool for the management of heterogeneous data, a series of links to additional digital contents has been implemented (F1).

Some of the links are general "buttons", which feature in the whole tour (Fig. 2), such as:

- "Forward" or "Back" options to explore the previous or the following scene, according to a pre-set sequence;
- "Info", which provides the user with a brief architectural and historical profile of the building;
- "Map", with localization of the building at territorial scale in a web map service (e.g. Google Maps, Bing Maps ...);
- "Plan", to navigate through the building's planimetric layout, where the user is able to see and access all the rooms/areas with a panorama, as well as to visualize dynamically his/her point of view while exploring the current scene.

Further links (Fig. 3) are specifically related to the entire current scene, such as:

- "Check-list", which contains schematic information on the construction materials and techniques;
- "Decay", which enables the visualization of the same scene, where cracks, humidity and surface alterations are mapped, using Adobe Photoshop ® CC, according to a pre-set legend of textures;
- "Videos", which show aerial shootings by UAVs, in this case by a DJI Inspire T600 drone equipped by X3 FC350 camera at 12.76 megapixel for speedy inspection of areas, which are of a limited accessibility.

Alternatively, there are geo-referenced hot spots associated with some elements of the current scene, such as:

- "Documents", which contain historical-technical data, including preceding surveys and/or interventions; and
- "Diagnostics", which have reports describing experimental set-up and results achieved by onsite non-destructive and locally destructive tests.

Furthermore, whenever the medium (T2) or high-resolution (T3) coloured point clouds/ texturized meshes are also available, for indirect or direct interrogation respectively (A2 - A3), the hot spot "3D model" is locally displayed.

In this connection, it should be outlined that the decay mapping, both in the thematic panoramic scenes ("Decay") and in the 3D models (section 4.2), is based on the taxonomy of the Italian code UNI 11182 "Cultural heritage. Natural and artificial stone. Description of the alteration - Terminology and definition", as well as on the international guidelines "ICOMOS-ISCS. Illustrated glossary on stone deterioration patterns”. However, in the present study, the textures, as reported in the code UNI 11182, have been changed with solid coloured layers, in order to make them more visible on the underlying image.

In order to show the above-mentioned specific contents, which are linked to the virtual tour, two representative situations are presented below, where the correlated analysis of different sources and gathered data has enabled the diagnosis of the occurring pathologies, paving the way for the following phase of monitoring and control in the form of the elaboration and interrogation of high-resolution coloured point clouds, as described in section 4.2.

The first situation (Fig. 3) concerns the pillars at the ground floor of the internal courtyard, which has been documented, not only by a series of panoramas at increasing heights, but also by video survey by drone-link “Videos”. For this situation, the coordinated and integrated assessment of historic data (hot spot “Documents”), damage patterns (link “Decay”) and ultrasonic tests (hot spot “Diagnostics”) has enabled the diagnosis of the nature and magnitude of the occurring buckling. In fact, the pillars, whose structural deficiency was already observed at the beginning of the last century, is still causing some typical deterioration phenomena, including vertical and hyperboloid cracks with missing parts at the corners of the stone blocks and poor compactness of the mortar joints, as classified by the related thematic panoramas (Fig. 4).

Moreover, this evidence is consistent with the results from the onsite investigation, as were documented in the enclosed diagnostic report. In fact, by accessing the report from the virtual tour, it is shown that on both the central pillars, a set of ultrasonic measurements was taken, following a semi-direct scheme, with n.5 acquisitions for each of the n.12 selected paths at different heights (Fig. 5) by the equipment Boviar CMS-V3H with 55 kHz high frequency emitter.

The displayed results, which were analysed for groups of measurements from similar paths, have enabled the identification of a great variability of the ultrasound travel velocity in the component (Fig. 6).

At a specific level, we are looking at the values from both pillars, which are very similar for materials and construction techniques:

- For the paths with receiver probe in “b” covering a single stone block, the average velocity is 6000 m/sec, with lowest values at around 4500 m/sec, corresponding to 25% reduction;
- For the paths with receiver probe in “c” crossing one mortar plane, the average velocity is 1500 m/sec, with lowest values at around 550 m/sec, corresponding to 65% reduction;
- For the paths with receiver probe in “d” intercepting two mortar planes, the average velocity is 1100 m/sec, with some values that could not be recorded because the signal failed to reach the receiver due to high attenuation.

Such a global response reasonably indicates that several cracks, which are visible on the external surface, correspond to internal fracture planes, with significant propagation even for the whole thickness of the component.

The second situation concerns the base of the main façade, where the thematic mapping of the stone decay – link “Decay” -, with great incidence of cavities, erosion and lacks, is compared against the thermographic survey, carried out by equipment FLIR T430s – hot spot “Diagnostics” (Fig. 7 and Fig. 8).

In fact, the enclosed thermograms show quite heterogeneous thermal behaviour in the scene. This is partially due to the difference between the calcarenitic stone of the base and the local tuff for the elevation. Nevertheless, the bossage is featured by several areas with low apparent temperatures, whose shape and extent are consistent with rising dampness of underground water.

This phenomenon is reasonably responsible for the visible alterations, since it triggers cycles of evaporation and absorption, with subsequent deposit of salts on the surface and increase of local mechanical stresses on the stone.

Both the situation, as assessed by correlation, and the integration of different documentary and experimental data (A1) within the virtual tour of panoramic scenes (T1) have been further studied by means of high-resolution 3D models (T3), as added contents for direct interrogation with the aim of monitoring and control of anomalies and pathologies (A3.1), as was also mentioned in the workflow of section 3.

In particular, some image-processing routines have been applied to 3D scanning point clouds, representing one pillar of the internal courtyard and a portion of main façade respectively, in order to assess the evolution in time of the decay patterns by extraction of metric data.

Fig. 2: Panorama of the entrance atrium, with general buttons as detailed in the legend on the right and active link to the building planimetric layout, which show both further accessible scenes and the current point of view of the users.

Fig. 3: Panorama of the internal courtyard on the ground floor

Fig. 4: Thematic panorama linked by the hot spot “Decay” in the scene of the internal courtyard – back view

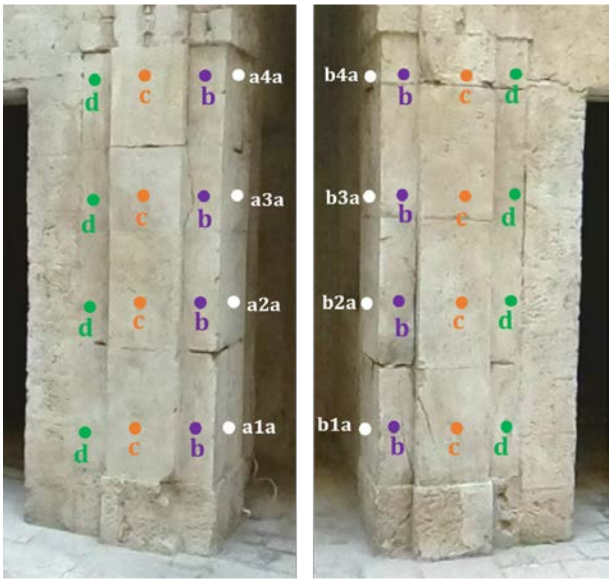


Fig. 5: Extract of the ultrasonic test report, which was accessible by the hot spot "Diagnostics"-scheme of the measurement paths connecting n. 4 positions of the emitter (white points) and n.12 positions of the receiver (purple, orange, green)

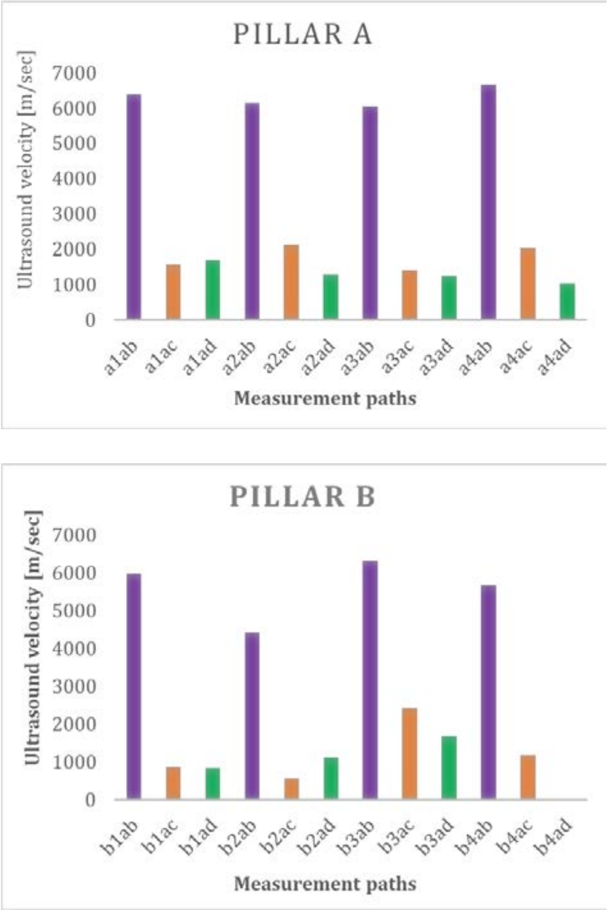


Fig. 6: Extract of the ultrasonic test report, which is accessible by hot spot "Diagnostics" – average travel velocities for each measurement path

Fig. 7: Visible and infrared picture of the basement accessible by hot spot "Diagnostics" – lateral view

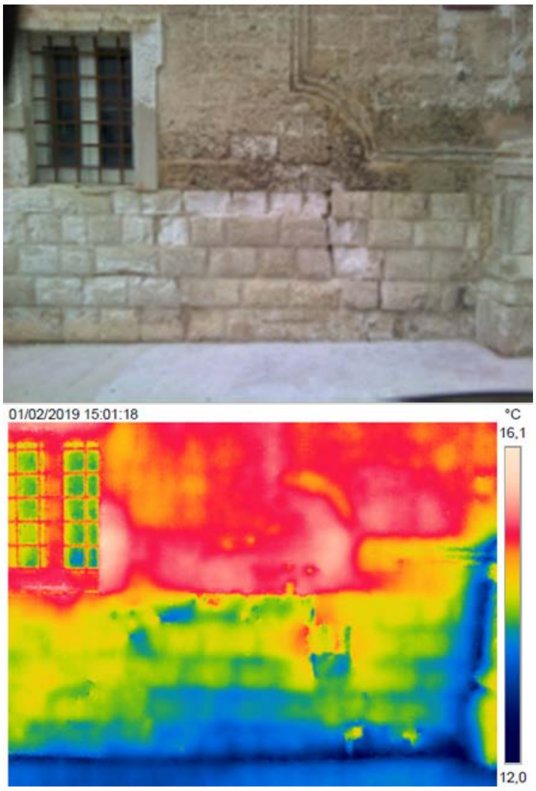


Fig. 8: Visible and infrared picture of the basement which is accessible by hot spot "Diagnostics" – front view

4.2 3D models for monitoring and control of pathologies

As previously introduced, in what follows a focus is proposed on the experimentation and validation of specific tools for three-dimensional models (T3) of limited areas of the case study, for assessment and control purposes, within a wider approach based on virtual tours of panoramic scenes of the whole architecture (T1). This investigation concerns the use of non-invasive procedures for the analysis and measurement of surfaces (F3.1), in order to identify, quantify and monitor physical alterations affecting a masonry (A3.1).

In previous works (Galantucci & Fatiguso, 2018; Galantucci, Fatiguso, & Galantucci, 2018), the authors identified an approach based on digital photogrammetry, to create 3D (dense point clouds, polygonal meshes) and 2D (high-resolution ortho-mosaics) models, to which they applied a series of algorithms or spatial and morphological filters, in order to extract quantitative information about visible alterations on a building façade. To quantify the decay, they adopted direct measuring instruments, such as computation of distances, areas, volumes and transversal profile extraction.

Further developments of this research highlighted the possibility to better exploit all information which a 3D model can provide for monitoring over time. For this purpose, it is fundamental to plan properly the photogrammetric acquisitions, predetermining the requested level of detail, from which it is possible to act on various scanning parameters (focal length, shooting distance, overlapping between images, number of images).

In particular, in order to achieve high-resolution 3D models, three ranges of decreasing shooting distances were considered, to which different 3D models' resolution magnitude corresponds:

a) Shooting distance (5-10 m) – 3D models' Resolution (0.5-1 mm / px)
b) Shooting distance (2-5 m) - 3D models' Resolution (0.1-0.3 mm / px)
c) Shooting distance (0.5-1.5 m) - 3D models' Resolution (0.01-0.1 mm / px).

Therefore, it is necessary to identify beforehand the purpose of the investigation through 3D models, in order to adapt the entity of the photogrammetric scans, because, for example, shooting distances of 0.5-1.5 m lead to extremely detailed models but also to a great number of images and long scanning and processing times.

Nevertheless, the employment of telescopic bars or drones equipped by cameras might be needed to ensure a desirable shooting distance. Moreover, regardless of the support, for the cameras it might be stated that:

In *a)* it is enough to adopt compact mirrorless cameras (Samsung NX 2000, Sony QX1) with wide-angle lenses (16-20 mm).

In *b)*, the acquisitions can be realized both with mirrorless cameras (Samsung NX 2000) or with reflex cameras (Canon Eos 760 D), with medium angle lenses (20-35 mm).

On the other hand, in *c)*, the acquisitions should be carried out with SLR cameras (Canon Eos 760D) and normal angle lenses (50-60 mm). A supplementary ring flash allows for better detection of the edges of a crack, by illuminating them.

With reference to the two situations presented in section 4.1, the experimentation was implemented on different samples of the right pillar of the internal courtyard (Fig. 3) and the main façade (Fig. 4). In this connection it is worth restating that, in the first case, a structural deficiency (vertical and hyperboloid cracks, poor mortar joints and missing parts at the corner of the stone blocks, etc.) was diagnosed, whereas, in the second case, a widespread surface degradation was connected to rising dampness (cavities, erosion and lacks). Scans were carried out with an increasing level of detail, in order to investigate these phenomena.

For the courtyard, the survey firstly concerned the entire façade corresponding to the access to the main staircase, with a shooting distance of around 10 m. Then, particular attention was dedicated to the pillars at the ground level, where significant cracks and lacks are located. The covered area, at the ground floor, is approximately 40 m^2, with a shooting distance of 5 m, and an overlapping of about 85% between consecutive images and 60% between adjacent lines. The resulting 3D models have comparable resolutions: 0,948 mm/pixel and 1,19 mm/pixel on the surface of the façade. The time-interval between the shootings was three years, from the first on 06/11/2015 to the last on 23/11/2018. Scans of the ground floor (main staircase) are useful not only to build an idea of the spatial location of different alterations, but also to monitor eventual changes which have occurred in the time interval. Furthermore, in 2018 the two pillars (right and left) at ground floor were acquired at 1.5 meters, in order to study alterations like cracks and to obtain quantitative information about them. In addition, in 2018, the widest hyperboloid crack (right pillar) was taken from 0.5 meters, with the aid of a ring flash, to detect crack edges precisely.

Table 1 summarizes the main scanning parameters for the façade and the pillars in the inner courtyard of Palmieri Palace.

On the contrary, for the external facade (covered area of 765 m^2), the adopted shooting distance was 10 m, with an overlapping of about 87% between consecutive images and 70% between adjacent lines. The two point-clouds, resulting from the acquisitions on 06/11/2015 and 09/06/2017, have a ground and height resolution respectively equal to 2.3 mm/pixel and 4.6 mm/ pixel in the first case and 2.4 mm/pixel and 4.6 mm/ pixel in the second case. The number of points is comparable to 960'000 pt in the first model and 951'021 pt in the second.

For the courtyard, at the ground floor, it was possible to realize all the scans through the work of a single person in about 3 hours, with the camera mounted on a tripod. Conversely, for the external façade, it was necessary to use the telescopic rod to reach the upper floors. The photogrammetric acquisitions were taken by two or three people in about three hours.

For both these situations, in order to follow monitoring goals and to estimate the evolution of damages over time, it was interesting to perform direct comparisons of 3D models of the same area, acquired in the aforementioned time interval, in the form of dense point clouds or polygonal meshes.

For this purpose, Cloud Compare was adopted, a software deriving from an open source project, consisting in a 3D point cloud (and triangular mesh) editing software, which was created for direct comparison between point clouds, for an easy observation of discrepancies and divergences. It is based on an Octree structure, which divides the three-dimensional space repeatedly into eight branches, starting from each internal node (Girardeau-Montaut, 2015).

To perform this kind of analysis, it is important to take into consideration two models which are characterized by comparable resolutions, i.e. analogous ground and height resolutions[1], and a congruous number of points, because, otherwise, the result of the detection could be affected by the divergence of the resolution.

First of all, it was necessary to align and register two models, choosing one of them as the reference (the one that doesn't move, during transformations). In the experimentation, the first model (year 2015) was considered as the *Reference* model and the second model (year 2017 or year 2018) as the *Compared* one, in order to understand the advancement of the alterations, and how they arise.

It was possible to align the two entities by picking three equivalent point-pairs on the object. To improve the alignment and to reduce the error, the two clouds were registered through the ICP algorithm (Iterative Closest Point), which consists in an iteration of a process to find the best match between the two clouds, which means minimizing the registration error (Root Mean Square Error or RMSE) until it is possible to find a pre-determined value (1).

$$RMSE = \sqrt{\frac{\sum_1^n (y_{ir} - y_{ic})^2}{n}} \qquad (1)$$

Where y_{ir} is the value of the point in the *Reference* model, y_{ia} is the value of the correspondent point in the *Compared* model and *n* is the number of points of the cloud.

Some main parameters were set in order to perform a better alignment:

- RMSE: $<10^{-5}$
- Number of iterations of the process: 20
- Final overlap of the 2 models: 100%

The aligned 3D models are useful to compute cloud-to-cloud (or cloud-to-mesh) distances, i.e. to calculate the deviation between two point-clouds (or between a point cloud and a mesh), through the 'nearest neighbour distance'. This consists of the Euclidean distance between the nearest point in the *Reference* cloud and each point of the *Compared* cloud.

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[1] Ground resolution: minimum distance on the ground between two closely located objects distinguishable as separate objects (parallel to the plane of the façade)
Height resolution: difference in height of the intersection of two homologous beams from adjacent photographs, when one of the two rays moves a pixel along the line connecting the two projection centres (perpendicular to the plane of the façade)

$$D = \sqrt{(p_x - q_x)^2 + (p_y - q_y)^2 + (p_z - q_z)^2} \quad (2)$$

In this formula *P(x,y,z)* is the point in the *Reference* cloud, while *Q(x,y,z)* is the correspondent point in the *Compared* cloud. If the *Reference* point cloud is not dense enough the computation of distances is not properly precise. Therefore, the distance (D) should be replaced by the distance between the point in the compared cloud and the distance of a mathematical model fitted on the 'nearest' point and several of its neighbours. The mathematical model better represents the surface, because it is independent of the cloud sampling, and it can be chosen by the user as the least square best fitting plane, as a Delaunay triangulation, or as a quadratic height function. It is important to underline that in all these computations the same roles (*Reference* and *Compared* model) of the clouds are retained. It is also possible to act concerning the way the neighbours are extracted around each 'nearest' point in the reference cloud, by setting a fixed number of neighbours, or by providing the radius of a spherical neighbourhood. The results of the computation can be observed as absolute distances or as distances split in the three dimensions (x, y, z) (Fig. 9).

Regarding the case study, in the first situation, for the pillars in the courtyard, the point clouds comparisons highlight a peculiar aspect concerning the correlation between resolution and purposes, in the application of the illustrated methodology.

From the comparison of long shooting distances models (10 m), nothing relevant emerges about the monitoring of the pathologies. On the other hand, models acquired from 5 meters reveal that the only perceptible alteration is a great lack, on the right pillar, in the correspondence of a mortar joint. In Fig. 9 a difference is visible from 1 cm to 3,5-4 cm. Conversely, for the crack in Fig.16 the only changes are located in those points near the edges, with a distance of 2-3 mm. These results are consistent with the ultrasonic measurements.

As far as the external façade is concerned, at a first observation, the areas are characterized by widespread degradation. It emerged that in a time interval of eighteen months (from 06/11/2015 to 09/06/2017), there occurred a progression of the detected alterations (Fig.10). The evolution of this situation is quite compatible with a phenomenon of rising dampness, which is also visible through other diagnostic analysis such as thermography. As an example, the greater distances (3,5-4,5 cm) are located near extended cracks, cavities, erosions and lacks, visible on the external surface, as demonstrated in 4.1 by a thermographic survey.

It is important to underline that, for monitoring purposes, in the application to the case study, the only comparable models were those which acquired shooting distances of 10 and 5 meters for the internal courtyard, and 10 m for the external façade, because they were the only available scans dating back to 2015. However, in 2017 and 2018, further acquisitions were taken: the survey campaign included short-distance shootings (from 1,5 to 0,5 m), from which it was possible to detect even small alterations such as small cracks (with an amplitude in an order of magnitude of few millimetres).

This leads to the consideration that, if the purpose of the investigation is a general mapping of the surface degradation and macroscopic alterations due to stone deterioration (lacks, erosions, ejection of material), in the order of magnitude of few centimetres, shooting distances from 10 m to 5 m are quite appropriate. Instead, if the purpose is to study and quantify pathologies such as cracks (whose width is usually around few millimetres), these distances are not suitable anymore, because the object of the investigation may be smaller or equal to the resolution of the model (few millimetres per pixel). It would be necessary to adopt smaller shooting distances (2-5 m). Finally, in order to analyse micro-cracks or mortar joint degradation, an even smaller shooting distance (0,5-2 m) is preferable.

Therefore, in the context of monitoring deteriorations that are visible on a building façade, the experimentation highlights the great potentialities of this technique, for a better comprehension of evolution over time, not only through quantitative information about geometric characteristics of the alterations detected (amplitude, depth, area), but also through direct comparison and computation of divergences in 3D models.

5. *Conclusion*

The present contribution set out to define and validate a methodological workflow on a specific case study, based on virtual tours of panoramic scenes, in order to provide an immersive environment for representing the entire building, collecting geo-referenced investigation data for the pre-diagnosis phase, and eventually for integrating 3D models for focused observations and measurements within the process of assessment and control of the state of conservation.

Tab. 1: Synoptic table, representing all the scanning and processing parameters related to the scans in the courtyard

Object		Entire Façade	Ground Floor	Right Pillar	Right Pillar
Date		06/11/15	23/11/18	23/11/18	20/12/18
Camera	-	NX 2000	NX 2000	NX 2000	760 D
Focal length	mm	20,00	20,00	20,00	60,00
Pixel Dimension	mm	0,00429	0,00429	0,00429	0,00408
Sensor Area	mm^2	368,95	368,95	368,95	332,27
Object Area	m^2	318,24	40	3	0,6
Actual Area	m^2	67,5	27	1,06	0,134
Shooting Distance	m	4,67	4,67	1,59	0,60
Overlapping between consecutive images	%	85%	86%	89%	80%
Overlapping between adjacent lines	%	59%	64%	57%	60%
N° Photos	-	170	40	26	107
Step in X	m	0,85	0,75	0,20	0,09
Step in Y	m	2,21	1,33	0,50	0,07
N° tie points	-	157.972	9.959	7.586	22.518
N° dense points	-	20.684.822	40.517.604	10.792.119	269.475.206
Processing Time	-	41’	37’	13h	16h4’
Ground Resolution	mm/pixel	0,948	1,19	0,326	0,0273
Height Resolution	mm/pixel	6,68		0,326	
Reprojection Error	pixel	0,808	0,715	0.423	1,04

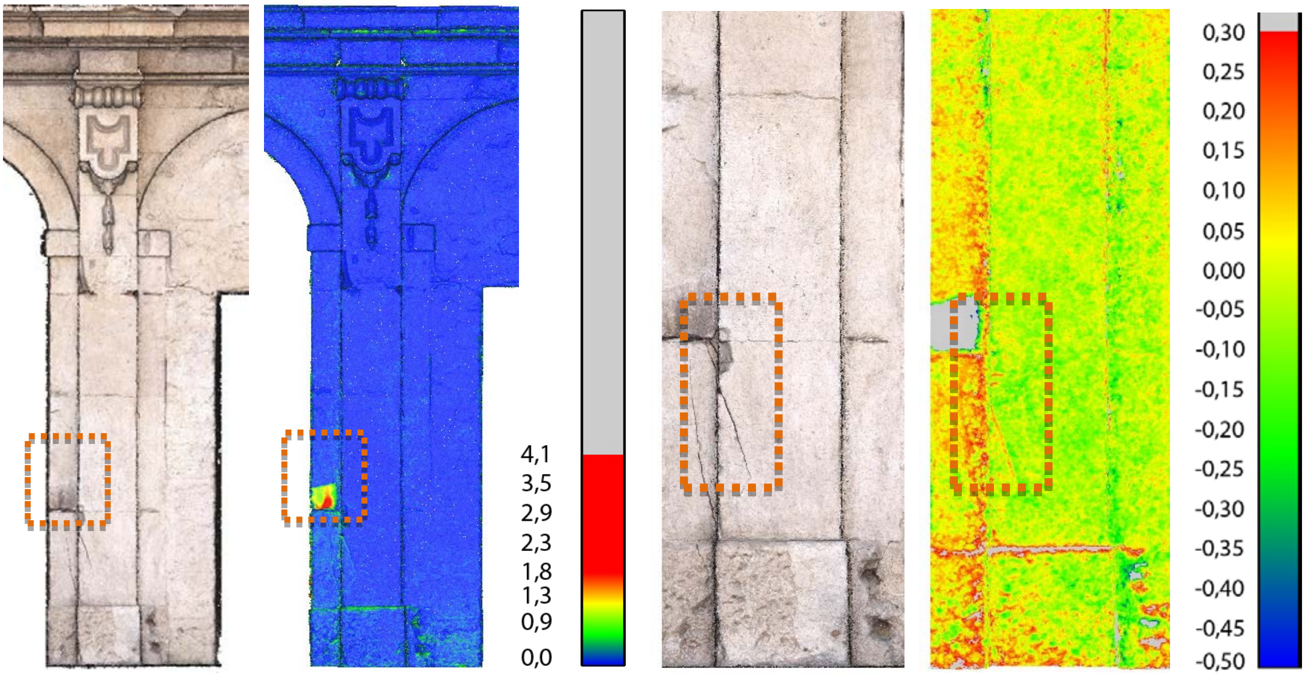

Fig. 9: Dense point cloud of the right pillar; false colour map representing the distances (cm) between the *reference* cloud (06/11/2015) and the *compared* one (23/11/2018)

In particular, the use of instruments with increasing operational complexity and the application to progressively restricted areas were proposed and discussed, in relation to more accurate phases of qualification, diagnosis and analysis.

The potentialities of immersive environments were explored in the form of virtual tours of 360 ° spherical photos of the entire building, to support visual survey activities, to detect characteristics and decay, as well as storage, sharing and consultation of analytical, documental and experimental sources, in the preliminary knowledge phase, through the examination of georeferenced links to external contents.

In addition, more complex elaborations, such as three-dimensional models, in the form of coloured dense point clouds, were outlined, in order to increase the level of preliminary knowledge to the level of consolidated knowledge, by creating ontologies for the analysis of spatial relations and semantic connections between elements. Metric and optical data were extracted, to monitor the evolution of pathological phenomena over time.

With reference to the last aspect, a photogrammetric campaign was also carried out, which aimed at understanding how 3D models can be exploited in order to support the achievement of deepened insights on the architectural artefact, at an advanced level of detail. Indeed, this analysis was realized on coloured dense point clouds of restricted critical areas, and they led to many conclusions.

The direct comparison of dense point clouds which was acquired within a time interval of eighteen or twenty-four months showed a progression of decay phenomena connected to structural deficiency (in the internal courtyard) and rising dampness (external masonry).

The outcomes of the experimentation and ultrasonic and thermographic investigations were also in agreement with these findings. Nevertheless, as mentioned in 4.2, it should be noticed that different levels of detail could be identified, connected to specific aims. Dense point clouds acquired at long shooting distances (5-10 m) are useful to obtain a first identification and mapping of the visible degradation on a masonry.

They provide an overall look about the general conditions of an artefact, in short shooting and processing times. 3D models corresponding to medium shooting distances (2-5 m) allow obtaining quantitative information on macroscopic surface alterations, through Image Processing techniques.

The only detectable alterations, at this level of detail, are the macroscopic surface ones: lacks, erosions, cavities, and material ejection. Instead, short shooting distances (0.5-1.5 m) are appropriate to detect smaller alterations, such as cracks, which are characterized by amplitudes even below the millimetre.

Finally, the overall analysis of the results underlines the need of a scalar and flexible approach for the management of the diagnostic process in the field of Architectural Heritage. These procedures should be implemented through logistic and operational tools, which are compatible with both immediacy and accuracy requirements, related to the complexity of the building, to its characteristics and decay, as well as to the purposes of the survey.

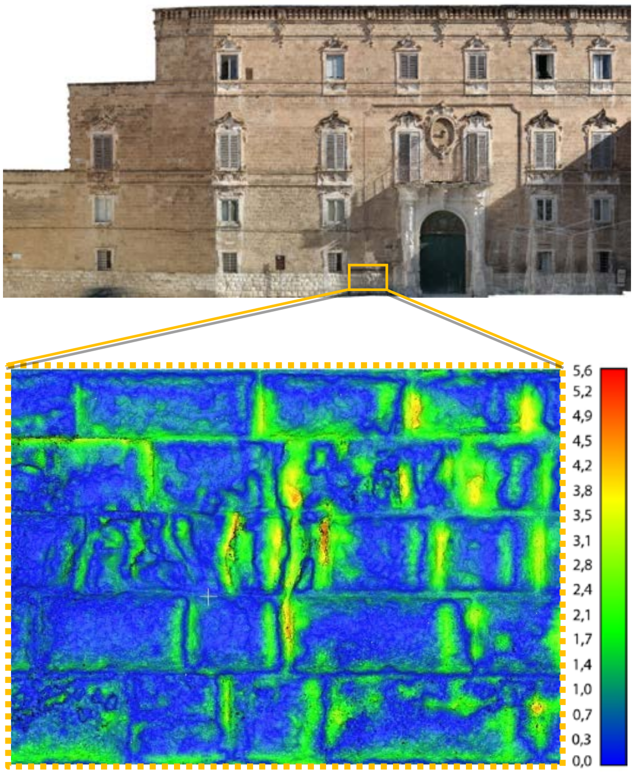

Fig. 10: Restricted area of the masonry, in the basement of the external façade (red rectangle); false colour map with absolute distances (cm) between the two point clouds (06/11/2015 - 09/06/2017).

REFERENCES

Agrafiotis, P., Lampropoulos, K., Georgopoulos, A., & Moropoulou, A. (2017). 3D modelling the invisible using ground penetrating radar. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, 42(2W3), 33–37.

Balsa-Barreiro, J., & Fritsch, D. (2018). Generation of visually aesthetic and detailed 3D models of historical cities by using laser scanning and digital photogrammetry. *Digital Applications in Archaeology and Cultural Heritage*, 8(2017), 57–64.

Barreau, J., Gaugne, R., & Gouranton, V. (2017). Immersive Point Cloud Manipulation for Cultural Heritage Documentation. *ERCIM News*, *ERCIM 2017*, 1–3.

Bruno, S., De Fino, M., & Fatiguso, F. (2018). Historic Building Information Modelling: performance assessment for diagnosis-aided information modelling and management. *Automation in Construction*, 86(2017), 256–276.

Cacciotti, R., Valach, J., Kuneš, P., Čerňanský, M., Blaško, M., & Křemen, P. (2013). Monument damage information system (mondis): An ontological approach to cultural heritage documentation. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 2(5/W1), 61–66.

Campanaro, D. M., Landeschi, G., Dell'Unto, N., & Leander Touati, A. M. (2016). 3D GIS for cultural heritage restoration: A "white box" workflow. *Journal of Cultural Heritage*, 18, 321–332.

Chane, C. S., Mansouri, A., Marzani, F. S., & Boochs, F. (2013). Integration of 3D and multispectral data for cultural heritage applications: Survey and perspectives. *Image and Vision Computing*, 31(1), 91–102.

De Fino, M., Scioti, A., Rubino, R., & Fatiguso, F. (2017). Qualificazione e valutazione di caratteristiche, patologie e prestazioni negli edifici storici mediante ambienti digitali immersivi. In G. Bernardini, E. Di Giuseppe (Eds.), *Colloqui.AT.e 2017 DEMOLITION OR RECONSTRUCTION?* (pp. 807-818). Monfalcone (Gorizia),Italy: Edicom Edizioni. .

De Fino, M., Scioti, A., Rubino, R., Pierucci, A., & Fatiguso, F. (2018). 'Augmented Diagnostics' for the Architectural Heritage. *International Journal of Heritage Architecture*, 2(2), 248–260.

De Luca, L., Busayarat, C., Stefani, C., & Veron, P. (2017). NUBES: describing, analysing, documenting and sharing digital representations of heritage buildings. In *Conference on Semantic 3D Media and Content.* Retrieved from HAL Id: hal-01174753 https://hal.archives-ouvertes.fr/hal-01174753

De Luca, L., Pierrot-deseilligny, M., Manuel, A., Chevrier, C., Lollier, B., Benistant, P., … & Alaoui, A. (2017). AIOLI. Retrieved March 17, 2019, from http://www.aioli.cloud/

Galantucci, R. A., & Fatiguso, F. (2018). Advanced damage detection techniques in historical buildings using digital photogrammetry and 3D surface anlysis. *Journal of Cultural Heritage*, 36, 51-62.

Galantucci, R. A., Fatiguso, F., & Galantucci, L. M. (2018). A proposal for a new standard quantification of damages of cultural heritages, based on 3d scanning. *SCIRES-IT - SCIentific RESearch and Information Technology*, 8(1), 121–138.

Girardeau-Montaut, D. (2015). CloudCompare v2.6.1 - User manual. Retrieved November 16, 2017, from http://www.danielgm.net/cc/doc/qCC/CloudCompare v2.6.1 - User manual.pdf

Girgenti, G. M. (2018). A virtual reconfiguration of two destroyed neighborhoods in the Old Town of Palermo. *SCIRES-IT - SCIentific RESearch and Information Technology*, 8(1), 93–104.

Guidi, G., Russo, M., & Angheleddu, D. (2014). 3D survey and virtual reconstruction of archeological sites. *Digital Applications in Archaeology and Cultural Heritage*, 1(2), 55-69.

Hallermann, N., Morgenthal, G., & Rodehorst, V. (2015). Unmanned Aerial Systems (UAS) – Case Studies of Vision Based Monitoring of Ageing Structures. In *International Symposium Non-Destructive Testing in Civil Engineering (NDT-CE)*. Retrieved from: https://www.ndt.net/article/ndtce2015/papers/169_hallermann_norman.pdf

Katz, J., & Tokovinine, A. (2017). The past, now showing in 3D: An introduction. *Digital Applications in Archaeology and Cultural Heritage*, 6(September), 1–3.

Koutsoudis, A., Vidmar, B., Ioannakis, G., Arnaoutoglou, F., Pavlidis, G., & Chamzas, C. (2014). Multi-image 3D reconstruction data evaluation. *Journal of Cultural Heritage*, 15(1), 73–79.

Kuroczyński P., Hauck O., D. D. (2016). *3D Models on Triple Paths - New Pathways for Documenting and Visualizing Virtual Reconstructions*. In M. Münster S., M. Pfarr-Harfst., & P. Kuroczyński (Eds.), *3D Research Challenges in Cultural Heritage II* (Vol. 10025). Cham, Switzerland: Springer.

Mandelli, A., Achille, C., Tommasi, C., & Fassi, F. (2017). Integration of 3D models and diagnostic analyses through a conservation-oriented information system. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, 42(2W5), 497–504.

Messaoudi, T., Véron, P., Halin, G., & De Luca, L. (2018). An ontological model for the reality-based 3D annotation of heritage building conservation state. *Journal of Cultural Heritage*, 29, 100-112.

Mohan, A., & Poobal, S. (2017). Crack detection using image processing: A critical review and analysis. *Alexandria Engineering Journal*, 57(2), 787-798.

Napolitano, R. K., Scherer, G., & Glisic, B. (2018). Virtual tours and informational modeling for conservation of cultural heritage sites. *Journal of Cultural Heritage*, 29, 123–129.

Nespeca, R., & De Luca, L. (2016). Analysis, thematic maps and data mining from point cloud to ontology for software development. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, 41(July), 347–354.

Pierdicca, R., Frontoni, E., Malinverni, E. S., Colosi, F., & Orazi, R. (2016). Virtual reconstruction of archaeological heritage using a combination of photogrammetric techniques: Huaca Arco Iris, Chan Chan, Peru. *Digital Applications in Archaeology and Cultural Heritage*, 3(3), 80–90.

Prati, D., Rrapaj, I., & Mochi, G. (2018). Contribution of parametric modeling in the interpretation of deformations and displacements of wooden trusses. *SCIRES-IT - SCIentific RESearch and Information Technology*, 8(1), 105–120.

Sánchez, J., & Quirós, E. (2017). Semiautomatic detection and classification of materials in historic buildings with low-cost photogrammetric equipment. *Journal of Cultural Heritage*, 25, 21–30.

Soler, F., Melero, F. J., & Luzón, M. V. (2017). A complete 3D information system for cultural heritage documentation. *Journal of Cultural Heritage*, 23, 49–57.

Valença, J., Dias-da-costa, D., Júlio, E., Araújo, H., & Costa, H. (2013). Automatic crack monitoring using photogrammetry and image processing, *Measurement* 46(1), 433–441.

Valzano, V., Negro, F., & Foschi, R. (2017). The Gallery of the Castromediano's Castle. Three-dimensional reconstruction and virtual representation. *SCIRES-IT - SCIentific RESearch and Information Technology*, 7(2), 13–26.