Joint Use of GPR Surveys, Terrestrial and Aerial Photogrammetry for the Study of the Portico of the Cathedral of S. Pietro (Isernia, Italy)

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Abstract. In the field of built heritage preservation, the contribution of non-destructive testing and 3D documentation represents a fundamental requirement for any project of maintenance and restoration, recording the state of conservation and enhancing irregular features. This paper presents the combined use of Ground Penetrating Radar (GPR) technique, terrestrial and unnamed aerial photogrammetry for the study of the portico of the Cathedral of S. Pietro (Isernia, Italy). It is an articulated construction, rebuilt several times over the centuries. The intent of the investigations was to offer a complete reconstruction of the architectural artefact and the morphology of the surfaces in order to guide and support strategic choices for the restoration and improvement of the building's seismic vulnerability, stopping the ongoing degradation phenomena. The results highlighted a series of critical issues such as the tilting of columns, the deformation of the morphology of the floor and the heterogeneous stratigraphy in some areas of the portico, which could affect the tolerance of the building to naturally induced flexural stresses.

Keywords: GPR · Terrestrial photogrammetry · Unnamed aerial photogrammetry · Aerial photogrammetry · Built cultural heritage · Cathedral of S. Pietro

The built cultural heritage is a trace of past human activities and an identity culture of a place. As it is very fragile, it must be preserved to avoid its irreversible loss. In dealing with these entities, one of the key requirement is the achievement of an adequate knowledge of the structures highlighting the basic building geometry, the internal composition of the materials (presence of cavities, foundations, alternation of different building materials, reinforcements) and any external irregular features such as material degradation, cracking, corrosion and tilting of vertical elements.

In recent years, scientific disciplines as geophysics and geomatics are widely applied in 3D documentation of historical building through a combination of technological systems for gathering, processing, modelling, analysing and representing all that is tangible and visible with what is hidden into the surfaces.

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Geophysics, in particular in the field of structural health monitoring, was proved an efficient way to obtain high-resolution diagnosis on small-sized targets immersed also in reduced portion of soil, surfaces or volumes. Thus, methods such infrared thermography [1, 2], sonic and ultrasonic tomography [3, 4], vibration-based methods [5] and ground-penetrating radar (GPR) [6–8] play today an important role in damage identification at a small scale of analysis regarding masonry walls, decorations and architectural elements. At a larger survey scale, methods such as seismic prospections [9, 10], electrical resistivity tomography (ERT) [11–13] and GPR surveys [10, 14, 15] are very efficient for site evaluation, mapping of soil and fill layers, foundation design, detection of cavities and underground structures, screening of floors and walls. Among these, GPR allows a faster data recording, a completely non-invasive diagnosis and high-resolution results.

On the other hand, geomatics allows the acquisition of geometric data that represent the reference basis for all the information acquired in the evaluation process of a building and gives high-resolution information about external signs of surface deterioration. In the last decade, the research on 3D survey has led to the definition of increasingly precise and realistic 3D digital models of archaeological objects and portions or entire architectural buildings through techniques such as digital (terrestrial and aerial) photogrammetry and 3D laser scanning. In any case, highly accurate point clouds are derived from the applications. Photogrammetry, compared to laser scanning, provides satisfactory results, is cheaper, is more portable and, in the case of the use of UAVs, guarantees a top view, which is very useful in the case of building surveys [16]. In literature, many cases of application of low cost image based surveys for building heritage are available [17–23].

The joint use of geophysics and geomatics is increasingly implemented in architectural heritage studies providing a complete analysis of an artifact [24–30]. Following this approach, in this paper, GPR, terrestrial and unnamed aerial photogrammetry were used for the study of the portico of the Cathedral of S. Pietro (Isernia, Italy) in the frame of a project of restoration and improvement of the building's seismic vulnerability. Being positioned on a complex archaeological stratigraphy, having had many interventions over time and showing some clear signs of decay, the investigation was carried out with the aim of a complete reconstruction of the architectural artefact and the morphology of the surfaces.

The overlay and the comparison of results led to the definition of some critical aspects to be taken into consideration in future restoration activities.

1 The Cathedral of San Pietro

The Cathedral of S. Pietro is located in Isernia (Molise, Italy) in the current Piazza A. D'Isernia where, in the basement, the ruins of the ancient city of *Aesernia* are preserved (Fig. 1 and 2). The archaeological area includes complex buildings, some of which were reused and incorporated into factories, which were rebuilt several times over the centuries. In this way, today, it represents a rich example of continuity of life characterized by structures from the Roman, early Christian and medieval periods [31–38].

In ancient times, on this area, the highest terrace of the town (432 meters a.s.l), the city forum was built. Certainly there were at least three temples concentrated here, two of which are preserved in the archaeological area while one is known only from literature,

located beyond the arch of S. Pietro, where the former episcopal seminary stands today [39].

Of the two temples still partially visible today, the largest had an extension of about 31 × 21 m (blue lines in Fig. 2), and the cathedral of Isernia, named after San Pietro, was then built on its structures. While continuing to use the podium and the access stairway, in the first centuries of Christianity, in fact, the temple was transformed in its spatiality and in its deeper meaning, by adding a terminal apse (orange lines in Fig. 2). In addition, it was equipped with a baptistery, excavated in the floor of the current left nave of the church. To the side of the remains of the main temple, under the courtyard of the episcope, there is the base of the other small temple (yellow lines in Fig. 2), only partially unearthed, oriented in a convergent way with the larger structure of the temple just described [40].

A small and underground room (probably a cryptoporticus, light blue lines in Fig. 2) that had an internal coating of polychrome plaster, the destination of which still appears unknown, located between the two temples, also belongs to this first phase of frequentation of the area. Furthermore, some large capitals, the Roman paving in large blocks of limestone between the two temples (dark green lines in Fig. 2), remains of cobblestone pavement (cyan lines in Fig. 2), terracotta pipes and substantial remains of an entablature are also visible. We also know by the local historian Ciarlanti in the seventeenth century that there were two imposing sepulchral monuments of important personalities, Sesto Apuleio and Settimio Muleio [39]. They were removed during the nineteenth century [41] and today the bases are preserved in the Museum of S. Maria delle Monache.

The discovery of a fair number of early medieval burials (magenta lines in Fig. 2), in which also elements of the stripping of classical monuments appear to have been widely reused, has given the certainty that the whole area was subsequently used for sepulchral purposes. In fact, in the archaeological area there are also several sarcophagi and a circular structure, made of irregular stone drafts, in which scholars have identified a probable furnace.

Presumably, around the fifth century, the Christian church was installed on the structures of the temple and this involved, among other things, the construction of a terminal apse and the baptistery. An imposing intervention of restorations affected the factory in the 11th century when it was rotated 180°, with the entrance towards the Piazza Mercato, i.e. Piazza A. D'Isernia, the hub of city life. Thus a basilica-type church was created, with a central nave and two side ones, continuous transept and terminal apses (magenta lines in the southern part of Fig. 2).

After the earthquake of 1456, the church was probably restored following the Gothic influences and then it was rebuilt again during the 17th century. Then, a protruding presbytery flanked by chapels replaced the terminal apse, the interiors were adapted to a classicist style and a portico on arches was built on the facade. An impressive campaign of works completely changed the appearance of the church between 1776 and 1789. Thus, a new interpretation of the building was proposed according to a late Baroque orientation, partially transforming the primitive layout. Decorations, new sculptures and paintings embellished the interiors but above all the plan of the building was completely modified. So the dome at the intersection of the central nave with the transept was constructed, the wooden ceiling was replaced with a vault in the central nave, domes in

the side aisles were constructed and the existing pillars were redesigned by introducing the Corinthian order. However, after a few years, on July 26, 1805, a strong earthquake seriously damaged the building and the roofs of the central nave, the dome and the portico collapsed. After various events, restoration work began in the middle of the century which gave the factory a new look according to the current neoclassical style and redeveloped the surrounding environment. In particular, the portico, built between 1847 and 1851, was designed with four large Ionic columns of about eight meters in height, enclosed by lateral walls, covered by a barrel vault and crowned by a frontispiece.

Almost a century later, further damage caused the bombing in 1943, which destroyed the entire right side of the building, its roofs and part of the portico which on that occasion was rebuilt without the lateral walls that enclosed it. From the post-war period to today, significant interventions have only affected the interior of the church. In the 1960s, marble and gilding were introduced to replace stuccos and frescoes; after the archaeological excavations of the 1980s the floor was redone, then changed again at the beginning of the 2000s according to a design that uses different types of marble, also recalling the division of the existing space in the coloring (Fig. 1).



Fig. 1. Location of Isernia on a Google Earth™ satellite image of Italy (a), detail of Piazza A. D'Isernia (b) and a picture of the Cathedral of S. Pietro (c). (Color figure online)



Fig. 2. Plans of the Cathedral of S. Pietro with indication of the archaeological remains relative to different construction phases. (Color figure online)

2 Methodology

2.1 Terrestrial and Unnamed Aerial Photogrammetry

In order to obtain a complete representation of the portico of the Cathedral of St. Pietro, unnamed aerial photogrammetry was integrated with terrestrial photogrammetry. Given the complexity of the building and above all of the ornaments, the choice of the two selected methods solves the need to reach high heights, in a short time, and with a good degree of accuracy. In a first phase, Ground Control Points (GCPs) consisting in chessboard-like targets were positioned on the paved surfaces according to a dense grid whose location was measured with the total station to determine their spatial coordinates. For areas that were not easily accessible because of the high altitude, geometric elements of the masonry were considered as references.

Surveying with a RPA Yuneec H20 (camera with CMOS sensor (1″), fixed focal length of 26 mm and resolution of 20 million pixels) was carried out with a manual flight control. The maximum flight duration was approximately 20 min. The images (nadiral and oblique) were acquired through a circular flight around the monument by varying the flight altitude and the distance from the cathedral. Ground photogrammetry was achieved using a Mirrorless Sony Alpha 5100, equipped of a CMOS sensor (23.5 × 15.6) with 24 million pixels and focal length 16–50 mm positioned on a telescopic pole. Frames were acquired along horizontal bands, ensuring an average overlap of 80% both horizontally and vertically. In this way, two data sets were obtained consisting of 117 frames for the drone survey and 123 frames for the survey with a digital ground camera.

Data processing of images was performed with Agisoft Metashape software (LLC, St. Petersburg, Russia) using the Structure from Motion (SfM) technique. The alignment of frames led to obtaining discrete point clouds (56.765 points for RPA survey; 125.383 for terrestrial survey) describing the object's starting geometry (Fig. 3a). In addition, the positions of the camera at the time of acquisition of frames and the internal camera calibration parameters (focal length, three radial and two tangential distortion coefficients with respect to a main point) were registered. Subsequently, the construction of the geometry was reached through the generation of dense clouds (3.378.208 points for RPA survey; 5.013.847 for terrestrial survey) (Fig. 3b). Then, the 3D model was georeferenced considering the surveyed GCPs. In this way, the alignment and the fusion of the two reliefs was achieved processing a unique and dense cloud consisting of 8.291.411 points (Fig. 3c). The average registration error was 0.009 m. Afterwards, the point cloud was transformed into a surface of triangulated points composed by 541.664 faces and 274.123 vertices (Fig. 3d). The "multi-resolution model", the "optimization method" and the "decimation filter" were applied respectively to adapt the discontinuities on the model, to smooth the nodes of the triangles and to simplify the model and generate a multi-resolution model. In the final step, the texture was constructed through the application of digital images to the model and metric and geo-referenced orthophotos were created.

Additional products derived from data processing are: the Digital Elevation Model (DEM) relating to the portico's floor (Fig. 3g), the vector representation of the facade (Fig. 3f) and sections of the columns (using CloudCompare software) (Fig. 3e) and calculation of deviations from the center of gravity (Fig. 4).

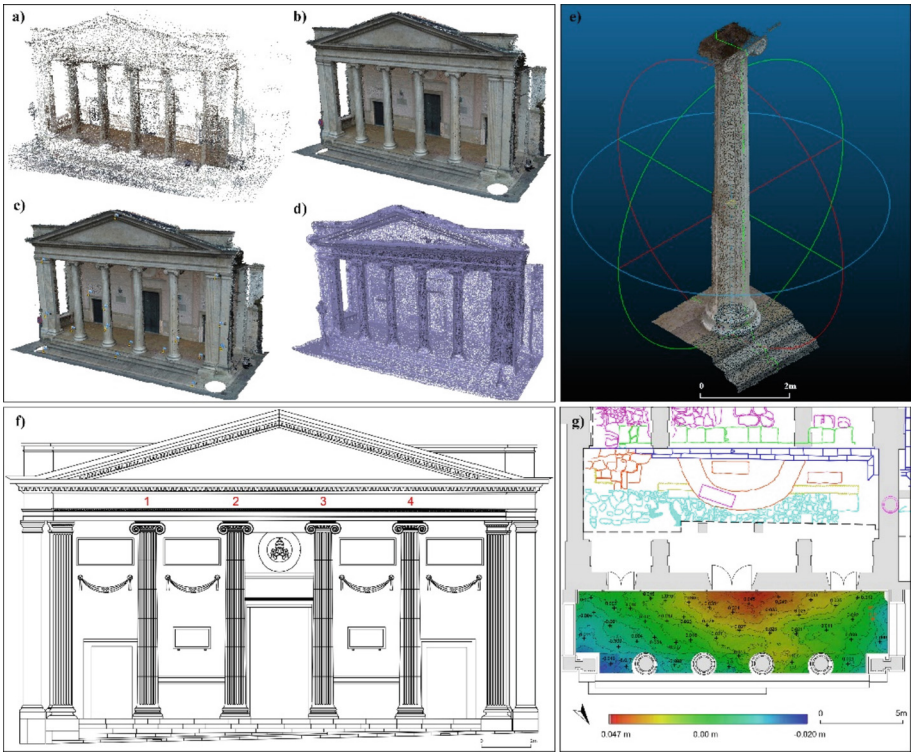

Fig. 3. Sparse point cloud (a), dense cloud (b), mesh RGB (c), solid mesh (d); 3D model of column used for extrapolation of sections using Cloud Compare (e); Front drawing of the building obtained from the photogrammetric survey (f); Digital Elevation Model of the floor with indication of the altitude (g).

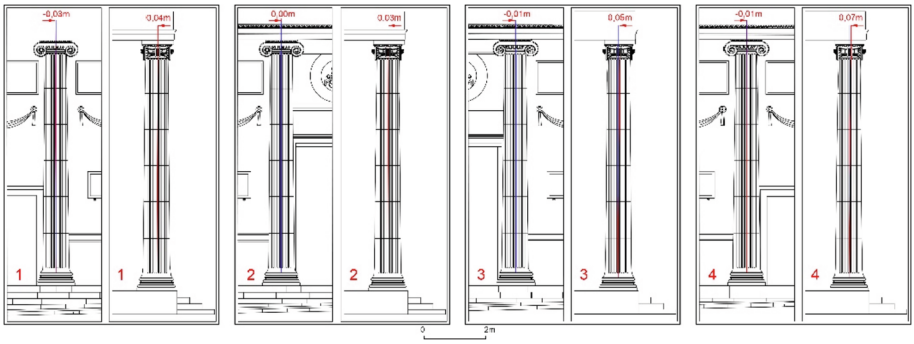

Fig. 4. Front (left) and side (right) views of columns.

2.2 Ground Penetrating Radar Survey

The GPR survey involved the flooring of the portico at the entrance to the church. The instrumentation used was the IDS RIS-K2 georadar with TRMF (200–600 MHz) multi-frequency monostatic antenna. Radar reflections on each line were recorded as 16 bit data in a time window of 90 ns, acquiring 512 samples per radar scan at 25 scan per mark (unit/marker, 1). Technically, data acquisition took place on lines where instrumental readings were performed continuously. The acquisition grid involved the creation of 20 longitudinal profiles (spaced 0.15 m apart) and 79 transversal profiles (spaced 0.3 m apart) with respect to the building entrance wall. The standard profiles representing the raw data were processed using GPR-SLICE 7.0 software through various processing techniques to emphasize the reflections coming from interfaces and buried objects: time-zero correnction, vertical band pass filters, background removal and automatic gain filters.

Finally, to verify the extension and size of the buried targets, the GPR profiles were inserted into a three-dimensional matrix from which sections were obtained, at a particular double time interval (measured in nanoseconds). A colour scale was assigned to the amplitude variation in the time-slices in order to show sufficient contrast and to make the anomalies easily recognizable: light green corresponds to low amplitudes, red to high amplitudes. Within the sections, low variations in amplitudes express small reflections that indicate the presence of fairly homogeneous material. High amplitudes, on the other hand, denote significant discontinuities in the investigated surface. Figure 5 shows the time-slices relating to the time intervals 14–22 ns and 29–37 ns.

3 Results and Discussion

The survey provided a precise metric and photorealistic determination of the complex structure resulting in a complete reconstruction of the architectural artefact.

From the detailed analysis of the documents, some irregularities in the arrangement of the columns emerge, resulting in slight deviations of the vertical axis from the center of gravity. In particular, in the frontal and lateral sections (Fig. 4) the following inclinations are noted: 0.03 m to the left (front) and 0.04 m towards the outside for the first column; in axis (front) and 0.03 m towards the outside for the second column; 0.01 m to the left (front) and 0.05 m to the outside for the third column; 0.01 m to the left (front) and 0.07 m to the outside for the fourth column.

Anomalies were also found in the morphology of the pavement which, according to the digital elevation model (DEM), presents an irregular slope in a spatial interval of 0.67 m (Fig. 3g). The lower points are measured between the first column and the left pillar while the highest points are located between the central entrance and the right side of the building, the latter distributed in such a way as to outline a semicircular prominence.

The GPR surveys have instead provided information on what is inside the surface of the pavement. The more superficial horizontal section (Fig. 5a) highlights the uniform presence of filling material with the exception of maximum signal amplitudes measured between the third and the fourth columns, which could be attributable to foundation

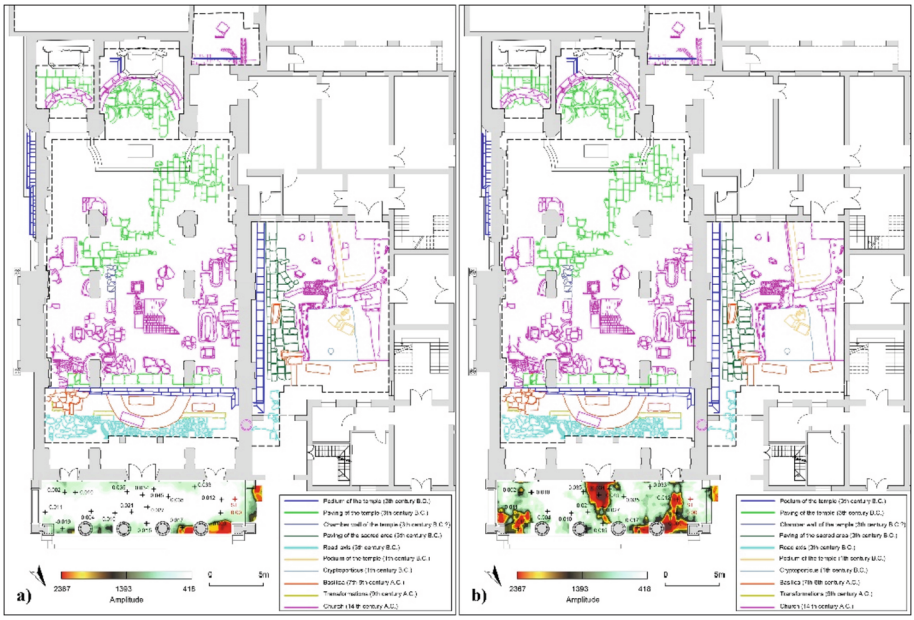

Fig. 5. Time-slice relative to the time window of 14–22 ns (a) and 29–37 ns (b) located on the plan of the Cathedral of San Pietro including the archaeological structures brought to light inside it over the years.

elements of the structure. However, this is not observed between the left pillar and the first column and between the first column and the second column.

The deeper section (Fig. 5b) highlights a semicircular anomaly, with a diameter of about 10 m, that is partially coinciding with the maximum values displayed by the DEM. Analyzing its shape, an apse, a funeral monument (like the Mausoleum of Caius Ennius Marsus in *Saepinum*, a roman town 30 km far from Isernia) but also structures of the *macellum* (a market where meat and fish were sold) or a *balneum* tank could be buried. In fact, according to Muratori, Garrucci and Mommsen [42–44], the existence in the forum, during the Augustan period, of a *macellum* with a portico and monumental entrance (*chalcidium*), a sort of covered market, built by Lucio Abullius Dexter, collapsed following the earthquake of 364 and then rebuilt at the expense of two citizens is known. Furthermore, a *balneum* and a temple with portico and kitchens, perhaps dedicated to Divus Julius, is remembered by an inscription still existing in the courtyard of the bishop's palace, adjacent to the cathedral, until 1847 [40].

To date we can certainly affirm that, if it was the foundation of an apse, it would fill that phase in the life of the building that goes from the 5th century to the 12th century approximately, integrating the knowledge that we have so far developed on the basis of the results of the previous excavation campaign. The construction of another church cannot be totally excluded, with a southern entrance as in the Christian church of the fifth century, following the strong earthquake of 847, which destroyed the city. This structure

may have stood until the earthquake of 1125 after which the medieval church was built. However, there are no archaeological data to support this hypothesis.

More likely, however, the hypothesis of a funerary monument with a cylindrical drum or part of the *macellum* is more realistic. Nerveless, the position of the structures behind the larger temple and in a secluded position with respect to the main road axis are currently difficult elements to be reconciled with the description we have of it, that is a factory with a portico and monumental entrance.

Of course, at this stage there are still few elements to support any hypothesis that it may be the structures of one of the buildings mentioned or even other constructions completely unknown to date. A more advanced stage of the work in the portico of the church, following a systematic excavation and the study of materials, could give rise to a reasoned architectural reconstruction.

4 Conclusions

The joint use of ground penetrating radar (GPR) technique, terrestrial and unnamed aerial photogrammetry for the study of the portico of the Cathedral of S. Pietro (Isernia, Italy) has offered a complete reconstruction of the architectural artefact. Evaluating the results globally, the non-verticality of the columns, considered individually, could be congenital (construction defects and/or structural interventions carried out in recent times and/or deformations caused by settling of the substrate) and not compromise the stability of the building. However, the data, combined with the deformation of the morphology of the floor, the absence of foundation elements on the left side of the building below the columns and the probable presence of archaeological remains only on the right side, could affect the tolerance of the building to naturally induced flexural stresses. In addition, the anomalies found by the GPR survey provided an important starting point of reflection on possible structures or monuments still buried in the subsoil that would enrich the knowledge of the complex archaeological stratigraphy of the building. Even if at this stage it was possible to formulate only hypotheses, the data acquired opens up new research directions.

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