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Geodatabase, metric reconstruction and a GIS platform of historical-archaeological sites in Aquino

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ABSTRACT
This paper presents the contents of a geodatabase developed from the outcomes of survey operations carried out, in several stages since 2015, within the archaeological context of the Roman city of *Aquinum*, in southern Lazio. The proposed geodatabase integrates traditional topographic surveying techniques with total station, GPS and GNSS geodetic receivers with photogrammetric surveys and terrestrial laser-scanner (TLS) measurements, including the realization of HBIM (Historical Building Information Modeling) models, to investigate some specific historical-archaeological evidence useful to understand the Roman and medieval urban structure of the city. The processing and management of the metric and information datasets were entrusted to a GIS platform, implemented in the opensource Quantum-GIS software, to optimize the flowchart of the acquisition/processing process and to realize an intra-site Web-GIS useful for the visualization and dissemination of the results. The methodological-operational approach applied in the research activities highlights the fundamental contribution that the technological innovations of geomatics can provide for the construction of elaborate knowledge concerning cultural heritage, also becoming the base for the elaboration of more complex and detailed analyses. In this case, for example, the HBIM digital model of the Church of Santa Maria of Libera was also used for an in-depth study in the field of structural engineering, as input to model the masonry vaults of the aisles of the church and assess their structural safety through the analysis methodology denominated "Thrust Network Analysis (TNA)." In addition, the high-precision 3D models developed from detailed photogrammetric measurements of the archaeological fragments and human remains found in the excavation areas made it possible to create interesting "visual digital products" that are immediately understandable even for non-experts, and thus particularly useful for wide-ranging knowledge dissemination.

Section: RESEARCH PAPER

Keywords: terrestrial laser scanning; close-range photogrammetry; point cloud; gis; modelling vaults; thrust diagram

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1. INTRODUCTION

In recent decades the steady advancement of geomatics surveying techniques has imparted a strong impetus in multiple research fields, foremost among them concerning the ways of knowing and analysing historical and cultural heritage. A variety of sensors have been used in the past for the documentation and monitoring of cultural heritage [1], [2], [3], [4], [5], [6], but the increase in the technological capabilities of geomatic sensors endorsed a quick development of virtualization processes of archaeological sites and architectural assets in a multi-temporal and multi-scale environment that is able to deal with the complexity and uniqueness of cultural heritage precisely through the processing, modelling, management, and dissemination of complex spatial and informational datasets. Geomatic sensors that today complement traditional topographic surveying techniques are not limited to red-green-blue (RGB) cameras and terrestrial laser scanners (TLS) used in close-range applications or underwater surveys [7], [8], [9], [10], [11], but also involve low-altitude sensors from unmanned aerial vehicles (UAVs) used increasingly in combination with multispectral cameras, Lidar and thermal sensors [12], [13], [14], [15], as well as the use of airborne and satellite sensors for macroscale site observation [16].

In the recent years, many studies explored these issues with particular emphasis on cultural heritage. For example, Agapiou and Lysandrou investigated how remote sensing has provided significant contributions to archaeological studies [17]; in [18], Tapete and Cigna studied the prospects of spatial SAR remote sensing for applications on large-scale archaeological-historical landscapes; in [19] Argyrou and Agapiou provided an analysis of the use of remote sensing technologies for archaeological applications through recent advanced image processing techniques; Luo et al. in [20] presented a detailed overview of the evolution of aerial and spatial remote sensing for cultural heritage applications. Additionally, there are numerous insights regarding specific techniques, such as those related to photogrammetric applications [21], [22], [23] or to the use of drones [24], [25].

Besides the significant improvement in terms of data accuracy, these new technological solutions are advantageous because they maximize the knowledge of the assets by obtaining precise and reliable interpretations while reducing the impact of costs and efficient use of time. They constitute a kind of new digital cultural ecosystem in which these tools foster knowledge of cultural heritage within a holistic approach that can relate geometric models to cognitive data also acquired from other disciplines, thus allowing decision-making processes to be better directed toward a conscious and sustainable enhancement of assets.

With specific reference to the archaeological field, such geomatic techniques allow to collect datasets not only on individual archaeological findings but also on the geographical contexts, evolving over time, in which they are embedded. The landscape in its multi-layeredness, in fact, represents direct evidence of how the tangible imprint of history is preserved, even latent, over time, despite the multiple natural and anthropic transformations of territories [26]. Therefore, in this perspective, the archaeological study of the historical landscape becomes an important opportunity for knowledge to link the historical contents detected to the metric definition of monuments and artefacts, so as to show their mutual relations in a map.

An essential part of archaeological data, in fact, is related to spatial information describing and classifying historical evidence, thanks in part to the increasing use of GIS software for collecting, entering, processing, cataloguing and editing such datasets. Indeed, they make it possible to implement advanced connections between graphical and textual data [27] while facilitating the correlation of information that, otherwise, would remain isolated and unhelpful to the overall understanding of the excavation under analysis [28], [29].

These programs have substantially altered traditional methods of investigation by fostering a multidisciplinary integration of expertise that has led to the development of several fields of application. Among the latter, a specific field of GIS application framed under "Landscape Archaeology" concerns the historical reconstruction of the territory through the recording, visualization, critical analysis and processing of historical and technical information acquired through field surveys and the study of ancient and documentary sources.

In a project of enhancement of the Cultural Heritage it is important to record in an appropriate historical documentation, topographic survey data, photogrammetry, and information about sites, excavations, and findings since accurate and complete digital documentation is a prerequisite for further analysis and interpretation.

The realization of point clouds by the terrestrial laser-scanning sessions and the creation of 3D models, as well as georeferencing by GPS and orthorectified images by digital photogrammetric acquisitions, are reserved for artefacts of greater importance, digital photogrammetry close-range for frescoes, and eventual casts by choosing, on a case-by-case basis, the technique best suited to the realization of the measurement and survey. However, some considerations and premises are necessary regarding the difficulties of the examined site, namely: 1) poor accessibility of the sites with field equipment for the possible installation of camera platforms, 2) presence of shaded areas due to different illumination generated by the vertical artefacts, 3) need for acquiring images to be reassembled later by mosaicking, 4) possibility of employing a lighting fleet to compensate for differences in illumination with the use of autonomous generators, 5) need to use, case by case, different optics in the measurement for automatically and arbitrarily scaling images, 6) need for a posteriori perspective correction of the image via software.

Within this methodological framework, this paper presents the contents of a geodatabase developed from the outcomes of survey operations carried out within the archaeological context of the Roman city of *Aquinum*, in Southern Lazio. Specifically, it is an activity carried out on several occasions since 2015, integrating multi-stage geomatic survey techniques (topographic, photogrammetric techniques, GNSS surveys, laser-scanning, GIS and BIM) to acquire metric and informative datasets, integrated with Quantum-GIS software for managing archaeological and spatial information useful to study the historical sites and investigate some specific historical-archaeological evidences of the Roman and medieval urban structure of *Aquinum*.

In the section 3.1 data from an integrated survey by using terrestrial laser-scanning and digital photogrammetry are analysed for the external part of the medieval Church of S. Maria della Libera with a particular emphasis to the realization of a HBIM of the church and a mosaic of the main portal. BIM model, considered as an archive tool of information from several sources, has the aim to experiment, through an illustrative case-study, the possibility to use spatial data surveyed by previous activities, geometric database and characteristics of materials in order to realize a model that, in the future, can represent a basis for safeguard interventions and securing of the historical building, for structural consolidation, conservative restauration, management of maintenance works and, also, for the dissemination of the historical-cultural knowledge on virtual platforms for the musealization and the spreading of the knowledge of the Cultural Heritage. As an example, it is worth mentioning the recent intervention in which terrestrial laser and scanning point clouds of the S. Maria della Libera Church have been used as input for a structural analysis, particularly for modelling masonry vaults, which characterize the roofing of the aisles of the church.

In the section 3.2 we illustrate the acquisition and elaboration of 3D models of additional archaeological evidence, such as the Marco Antonio's Roman Arch, extraordinary honorary monument traditionally dated to the 1st century BC, connected in a suggestive way to a corner of the Church, the Porta S. Lorenzo, the ancient Via Latina, georeferenced by GPS system and surveyed by digital photogrammetry for multiple study objectives documented in previous papers recalled in the references.

The section 3.3 refers to a campaign of digital photogrammetry close-range held in September-October 2015 which has unearthed archaeological findings in the ancient *Aquinum*, along via Latina Nova, in the S. Pietro Vetere site. Objective of the first excavation campaign has been the interpretation of the findings, which has allowed us to obtain a sequence of useful elements to study the urban planning of the

Roman town first and, subsequently, of the medieval *Aquinum*, since nowadays contrasting theories do exist on its evolution. Preliminary activities of surveying refer to the ruins of a medieval church dedicated to the worship of S. Costanzo. A further aim of this aspect of the research is to supply the digital close-range photogrammetry, using innovative techniques and software for generating the 3D surface which allows us to reconstruct three-dimensional models which can be used also for 3D printings or models by Computer Numerically Control machines (CNC), as in the case of the ancient mosaics and frescos.

Therefore, in sections 3.1, 3.2, and 3.3, survey activities and accurate, multi-temporal and multi-scalar processing of historical artefacts and archaeological findings are described, to provide the basis of an integrated project on advancing knowledge of the history and evolution of ancient *Aquinum.*

In a future perspective of integrated project on the history and evolution of the ancient *Aquinum,* the ensemble composed of the surveyed stretch of the Via Latina, Porta San Lorenzo, the Church of Santa Maria della Libera, the adjacent Arch of Marco Antonio, the archaeological evidence from the excavations in San Pietro Vetere site and, also, the municipal archaeological museum “Khaled Al Asaad”, can be framed in an unitary context and connected to Medieval village and to the monumental-natural park of the Vallone of Aquino. This highlights the urge of a plan of restoration and valorisation of the heritage, of the historical memory and of the values embedded in them.

Finally, recent developments in Geomatics concerning increasingly sophisticated techniques for the classification, cataloguing, management and dissemination of archaeological data has led to a substantial change in the procedures for study and research in the field of Cultural Heritage. The possibility of managing a completely digital workflow, from the excavation phase to the data recording and analysis phase, opens new perspectives in the field of dissemination and research in archaeology. At the same time, new challenges arise on the standardization of digitization procedures of spatial information and archaeological data, as well as in the organization of the same for the purpose of spatial and topological analysis using opensource GIS software.

2. THE CASE-STUDY

Located along the historic route of the Via Francigena that allowed pilgrims to reach Rome across the Alps, the city of Aquino is nowadays famous mainly for being the birthplace of the Catholic Church theologian and philosopher, Thomas Aquinas. Although the exact date of foundation is not known, the evolutionary history of the city is particularly complex in relation also to the environmental transformations that, over the centuries, strongly modified the territorial context in which it is set. Developed over time on the site of a pre-Roman settlement located on a travertine platform dedicated to quarrying stone materials in the Vallone delle Pentime, the urban core was in fact bordered, to the east, by three large lakes (one defined in some documents as Lake Maggiore and two others of smaller extension) that have now disappeared altogether but whose ancient presence is still recognizable from the morphological analysis of the territorial context.

The general framework of the GIS map in Figure 1 shows: in pink, the territory occupied by the ancient urban area of *Aquinum* bordered on the eastern side by a moat overlooking the three ancient lakes mentioned above, shown in light blue; in light yellow, the area of the Lombard settlement occupied by the late 6th century AD; in light ochre, the presumed presence of a monumental necropolis that extended outside the urban core along the Via Latina.

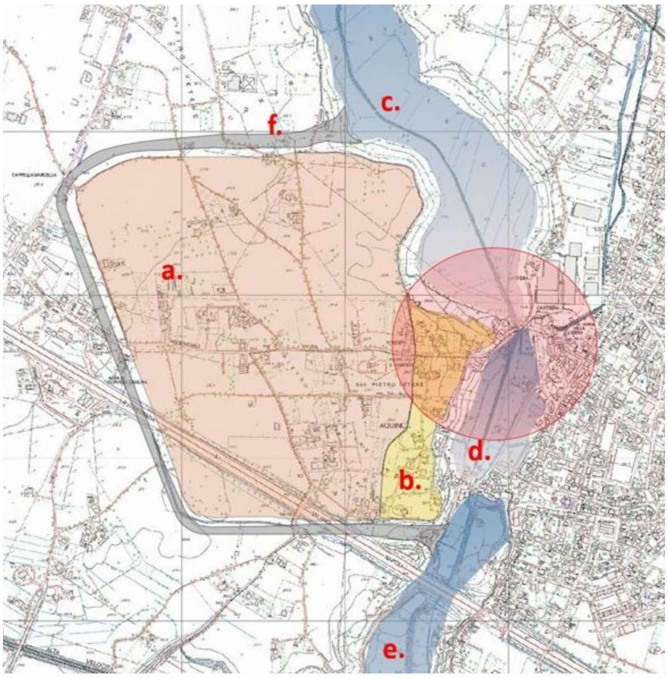


Figure 1. GIS snapshots, basemap CTR 1:5000. a. Ager romano; b. longobard village; c.,d.,e, ancient lakes; f. ancient moat. Circled in red is the area under study (cfr. Figure 2).

Historically, the urban area of Aquino is first documented in Roman sources from 211 A.D. onwards, defined as a municipium and later as a colony of "triumviral" foundation. The large area of the city (about 100 hectares) was enclosed by a walled circuit crossed by the ancient Via Latina with a perfect east-west orientation, bordered on the western and eastern sides by two gates, now known respectively as Porta Romana and Porta San Lorenzo (now Porta Capuana).

Within the urban core there had to be numerous valuable architectural evidence, some of which, although transformed over time, have been partially preserved to the present day. Among these, the best-preserved building is surely the church of S. Maria della Libera, erected in the late 10th century AD in a very scenic location. The facade, which dominates a flight of steps from the top, is monumentalized by a portico and bell tower and is decorated with numerous spolia, architectural and sculptural pieces from ancient monuments. Another important monument is the so-called Arch of Marco Antonio, now partially buried due to hydrological events that probably occurred in the Middle Ages. It is one of the earliest examples of that category of monuments intended to celebrate important personalities and, at the same time, to emphasize the distinction between urban and extra-urban space: thanks to a reference in ancient sources (*Cicero, Philippicae* 2.41.105-106) and comparative studies, in fact, the arch seems to date from the period of the triumvirate (around 40 BC).

After the Roman period, one of the most important moments in the urban-territorial transformation phases of the cities probably began during the 10th century with the translation of the urban built-up area to the opposite bank of the Vallone where a castle (*praetorium aquinense*) was built, from whose subsequent expansion, represented first by the medieval village, and then by the modern city developed [30].

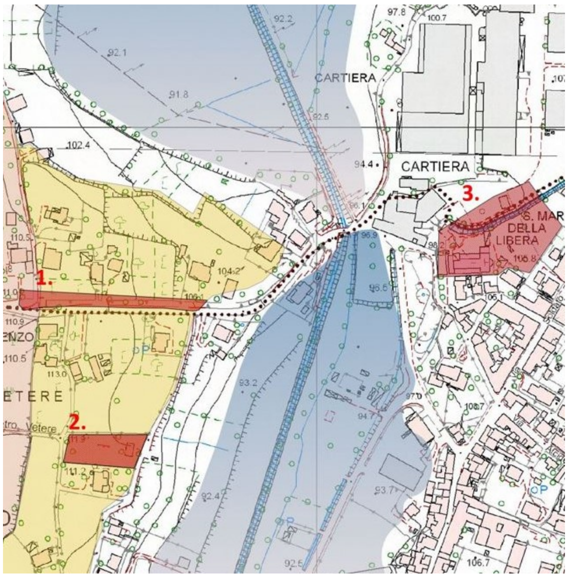


Figure 2. Areas covered by GPS and photogrammetric survey and TLS. 1. Porta S. Lorenzo and Via Latina; 2. Excavations S. Maria degli Angeli Church; 3. S. Maria della Libera Church and Marco Antonio Arch.

As shown in Figure 2, during these repeated phases of urban transformation numerous remains of the Roman-established town were reabsorbed into the new medieval core. One of the most obvious evidence of the passage of the civic centre from one side of the valley to the other one is precisely the Porta Capuana, or San Lorenzo gate, believed to be of Roman origin but now variously dated between the 2nd century B.C. and the medieval-Federician age. In addition to the gate, on the plain of San Pietro in Vetere other remains have been unearthed: among them also the remains of the church of Santa Maria degli Angeli, Aquino's probable second cathedral originally consecrated to San Costanzo, have been revealed.

3. DATASET ACQUISITION

To have a complete overview of the multiple geomatic survey activities conducted between 2015 and 2018 on the plateau of San Pietro Vetere by a team of researchers and already published [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41] the main outcomes are brought together, including those surveyed by the first author of the present paper, at that time working at the University of Cassino and Southern Lazio, in collaboration with archaeologists from the Romanian University of Babes-Bolyai in Cluj-Napoca, scholars from the Romanian Embassy in Rome and the Khaled Asaad Municipal Museum in Aquino.
The above mentioned surveys were data acquisition campaigns that integrate traditional topographic survey techniques with total station, GPS and GNSS geodetic receivers to photogrammetric surveys and measurements with terrestrial laser-scanner (TLS), for the metric reconstruction of a section of the ancient Roman Via Latina (of the Porta San Lorenzo), the survey of the Arch of Marco Antonio and the monumental complex of the church of S. Maria della Libera (also with the realization of an HBIM model), the study and geometric-dimensional restitution, also in 3D, of two areas of archaeological excavation with the related remains found.

The processing and management of these datasets have been entrusted to a GIS platform, implemented in the opensource software Quantum-GIS, with the intention of optimizing the flowchart of the data acquisition/processing process, shown in

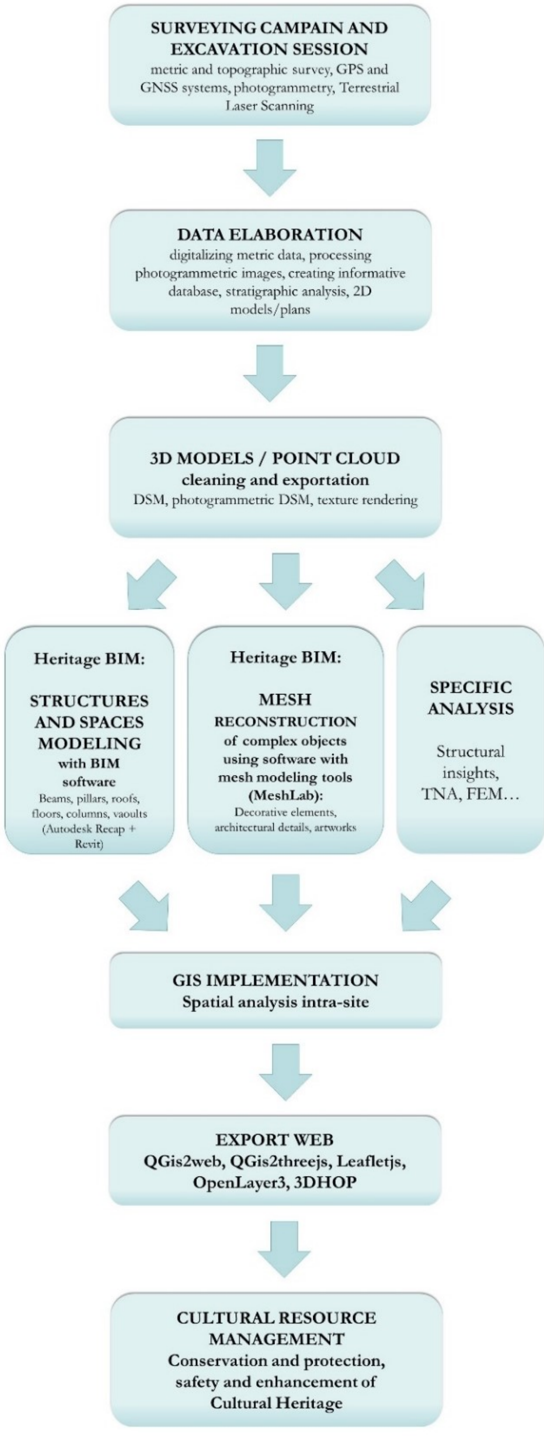


Figure 3. Flowchart of analysis phases.

Figure 3, and, at the same time, realizing an "intra-site" Web-GIS useful for visualization and dissemination of the results. "Intra-site" spatial analysis constitutes a relatively new application of geographic information systems to the needs of archaeological investigation of restricted excavation areas. In Italy, the first experiments date back to the second half of the 1990s and are distinguished from traditional GIS spatial analysis functions by a more complex methodological and analytical approach that requires a greater focus on the survey, study and digital conversion of multitemporal and multiscale datasets derived by the integration of different geomatic survey techniques. Additionally, special importance is reserved to the choice of the most effective stratigraphic representation modes to visualize the location of the surveyed artefacts and stratigraphic sequences concerning a restricted geographic scale. In summary, this is a platform that, by bringing together all the metric and information data collected, can also be useful for future land-use planning strategies, in terms of enhancing and securing the heritage, historical memory and identity values guarded by such evidence.

3.1. Chiesa di Santa Maria della Libera: TLS acquisition

Within the study area, the most important architectural evidence is the church of Santa Maria della Libera, a monumental complex with a rectangular layout with internal dimensions of 17 × 38 meters and dating back to 1000-1100 AD [42]

As shown in Figure 4, an imposing staircase precedes the entrance portico characterized by three round arches sixth on which are set three bays with an almost square plan. Through the main portal surmounted by a lunette decorated with mosaics, one enters the interior space of the church, consisting of three rectangular naves separated by two sets of square pillars and closing on three semi-circular apses preceded by a transept that is reached by passing through the imposing triumphal arch resting on pilasters culminating in fragments of Roman cornices that serve as capitals. In the centre there is the main altar, consisting of a Roman marble sarcophagus; the nave has a wooden roof, while the side ones have several cross vaults.

The clear Romanesque style of the church is recognizable also by the use of the typical local soft travertine, probably fragmentary material obtained by the remains of Roman buildings surrounding the area where the complex was erected.

The survey of the Church of Santa Maria della Libera was carried out, both internally and externally, integrating different techniques: the TOPCON - GLS 2000 laser station, which, thanks to 18 scans, provided a dense cloud of 3D points (about 5 million points), thus achieving an accuracy of one millimetre; GNSS systems for surveying a network of GPS point references useful for the survey and reciprocal positioning of the sacred building and the evidences in its immediate circumstances (such as the Arch of Marcus Aurelius); and numerous photogrammetric shots of both the main elements of the sacred building and the surrounding context [34], [38].

Figure 4. S. Maria della Libera Church.

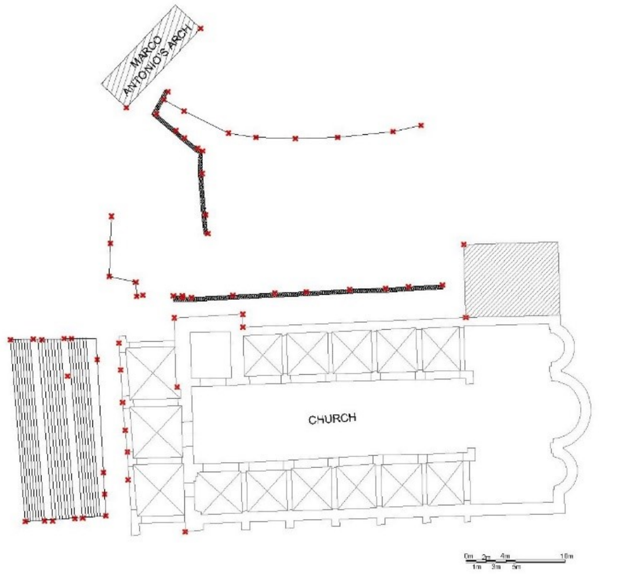


Figure 5. Plan of the monumental complex of Santa Maria della Libera and Marco Antonio's Arch extrapolated from the TLS survey.

For the integration of the different survey methods, targets were applied at the points of the monuments with the aim of the photogrammetric survey, the exact location of which was measured with GPS (points highlighted in red in Figure 5).

With specific reference to the Church of S. Maria della Libera, the objective of the geomatic survey activities of the Church of S. Maria della Libera was the construction of a Historic Building Information Model (HBIM) as a "ready-to-use" model in which the different available databases, ensuring interoperability with a high level of reliability, were collected.

For the construction of this HBIM model, the point clouds (Figure 6) were processed through Autodesk Recap software to remove any "disturbing elements," such as vegetation, road elements, and people, and thus retain only the architectural elements useful for the subsequent stages of actual modelling. The latter began with the subdivision of the point cloud into diversified partial areas to independently identify some important architectural elements such as the front access staircase, the main access portal, the buildings adjacent to the access portal, the buildings adjacent to the church, Marcantonio's Roman arch bridge, and the remaining surrounding area. Once the overlaying stages were completed, the point cloud was processed in 3D using Autodesk Revit software (Figure 7 and Figure 8), to initiate geometric modelling of the BIM model suitable for including the main masonry walls, openings, and reference elevation levels, and MeshLab software (Figure 9), for surface mesh extrapolation regarding some particular elements such as vaults, capitals, bas-relief decorative elements, lunettes, and entablatures of the church [40].

The church of Santa Maria della Libera has some valuable elements in the details of the main portal, enriched by several "spolia" from the surrounding burial areas of the Roman period, composed of five fragments related to a large frieze with acanthus spirals datable to the first half of the first century AD. Particularly significant is the lunette above the lintel of the portal, with a mosaic depicting Mary with Baby Jesus between two noblewomen, whose imprinted names are, Maria and Ottolina, represented in sarcophagi. The uniqueness and richness of these details were highlighted by another photogrammetric survey carried out using an H6D-400C MS camera with a 100 Mpx

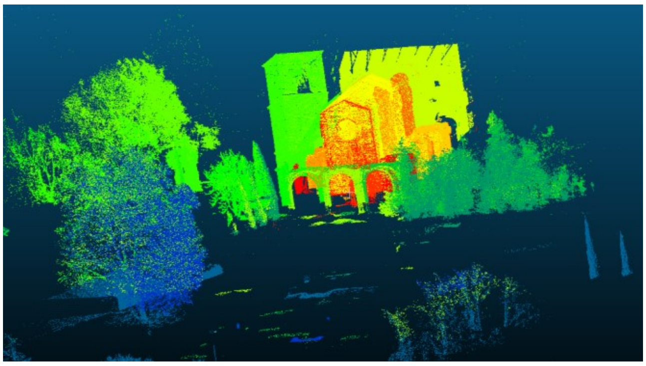


Figure 6. Dense Point Cloud.

Figure 7. Point cloud dataset visualization.

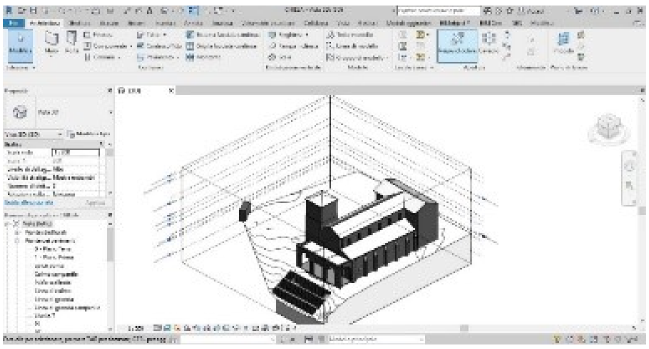


Figure 8. HBIM model.

CMOS sensor. These images were orthorectified through DXO software, using the control planes surveyed by laser technique (Figure 10). A 3D model of the single gantry, with an accuracy of a few millimetres, was obtained through image processing performed with Agisoft Photo-scan software.

To make further comparisons, 55 control points were fixed on the gantry, and through the Leica Disto D3 laser distance meter, their relative distances were surveyed, aimed at unambiguously describing their geometry. Of these 55 points, 5 (Nr. 1, 5, 23, 29, 50, respectively) were used as markers/support photogrammetric points, and the surveyed relative distances were entered manually as references using the scale in the two software (DXO and Agisoft) used for image processing.

Comparing the measurement values obtained from the two models using DXO and Agisoft software, the measurement errors range from a few millimetres to a maximum of 1 centimetre, with a standard deviation of 0.01 m (DXO) and 0.009 m (Agisoft), respectively.

The great advantage in the use of these geomatic surveying techniques lies in the possibility of using the point clouds for multiple multidisciplinary analyses: in this case, for example, the

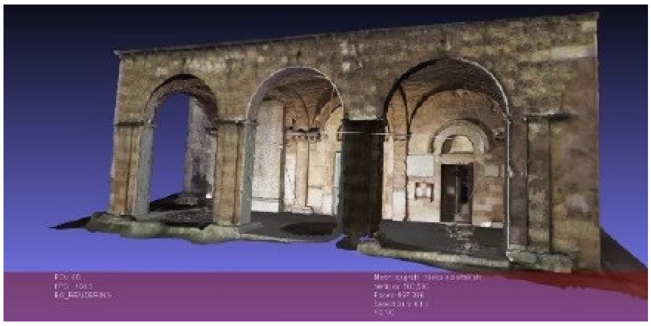


Figure 9. Mesh of the Church portal returned in Meshlab.

Figure 10. Main portal of the Church of Santa Maria della Libera: rectified orthophoto-plan obtained using DXO software, showing control points subject to direct survey.

datasets obtained from the terrestrial laser scanning of the Church of Santa Maria della Libera were also used for in-depth study in the field of structural engineering, as input to model the masonry vaults of the church's aisles and assess their structural safety.

As evidenced by the model prepared in Mc-Neel Rhinoceros with an accuracy on the order of ± 20 millimetres (Figure 11), these are cross-vaulted systems with a square base of about 4 meters side and 2 meters height, with a thickness of 45 cm, consisting of soft travertine with a specific gravity of 2.72 t/m^3. The general static model of these vaults is quite simple: two load-bearing diagonal arches unload loads onto four pillars at the

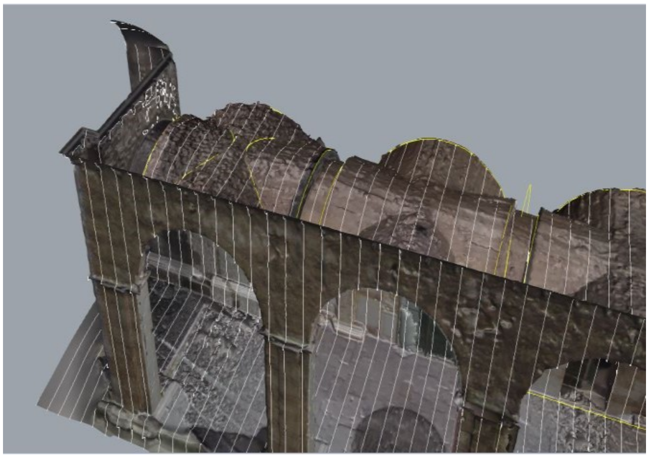


Figure 11. Extrapolation of the sections in Mc-Neel Rhinoceros.

vertices, which, in turn, support the four ribs of a barrel vault as a succession of smaller and smaller arches from the outer perimeter toward the centre. Each arch transmits its connected thrust to the diagonal arches; thus, the diagonal arches are loaded by the combination of the forces they support.

Finite element analysis is usually considered the best numerical technique for structural investigation since it can handle the characteristic parameters through geometrically complex 3D models and allows multiple analyses (linear, nonlinear, dynamic, etc.) to be performed on the same structure. However, in the case of historical monumental masonry heritage, FEM analysis has some limitations. These problems are mainly due to the difficulty in knowing and describing both the mechanical parameters of the constituent materials of the structure and the effects produced by the multiple transformative interventions that have occurred over time. To overcome these limitations, an alternative analysis methodology called "Thrust Network Analysis (TNA)" has been developed, as already described in [38], [39]. This is a recent method that can be considered an automated computational variant of the Mery method used for manual calculation of masonry arches. Specifically, TNA models masonry vaults as a discrete network of branches, subject only to compressive forces in equilibrium with gravitational loads. This analogy, called the "catenary principle," is that of an arch resembling a long chain held at its ends and left dangling. Heyman in [43] mixed this principle with the limit analysis theorems of plasticity, with the static one, to assess the safety of masonry structures by predicting the ultimate mechanism of 3D arches or framed structures. A first extension of this approach to vaulted and domed systems was proposed in [44] by O' Dwyer by fictitiously deconstructing the structure into discrete arches in equilibrium, i.e., by searching for force networks within the structure by applying precisely "Thrust Network Analysis (TNA)."

Following this method, the equilibrium of the vaults can be studied by considering the thrusts, that is, the compressive forces that balance the loads applied within the structure. As shown in Figure 12, this network, called thrust network, is described by N_n nodes and N_b branches connecting pairs of nodes. The i-th node of the network is defined by its position (x_n; y_n; z_n), in a 3D Cartesian reference system, where z is the vertical direction.

The concentrated force at each node is indicated by

$$f^{\mathrm{n}} = \left(t_x^{\mathrm{n}}; t_y^{\mathrm{n}}; t_z^{\mathrm{n}}\right), \qquad (1)$$

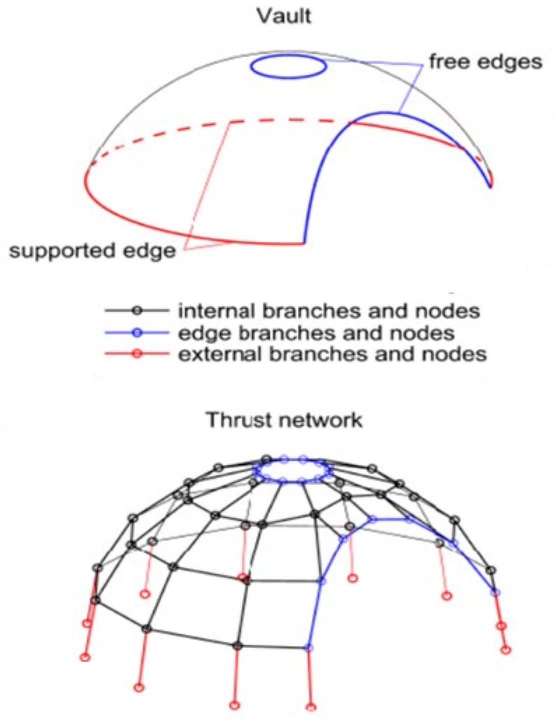


Figure 12. Modelling of the vaults.

while the generic network branch b is identified by the two end nodes and the corresponding thrust value T^{b}:

$$T^{\mathrm{b}} = \left(t_x^{\mathrm{b}}; t_y^{\mathrm{b}}; t_z^{\mathrm{b}}\right). \qquad (2)$$

The geometric location of the nodes p(n) is described in terms of abscissae and ordinates, while the vertical position is evaluated such that the height of the free nodes is contained in the width of the vault. In particular, the maximum height of the nodes is associated with the minimum thrusts and vice versa. Thus, the TNA method proposes the calculation of equilibrium conditions to evaluate the thrusts in the branches, the heights of the inner and outer nodes, and the position, in the horizontal plane, of the nodes belonging to the free edges of the vault (Figure 13).

The equilibrium equation of the generic node of the vault is given by the relation:

$$\sum_{\mathrm{b} \in B} T^{\mathrm{b}} I^{\mathrm{bn}} + f^{\mathrm{n}} = 0\,, \qquad (3)$$

where T^{b} is the thrust of branch b and I^{bn} is the unit vector parallel to b and facing n:

$$I^{\mathrm{bn}} = \frac{i^{\mathrm{bn}}}{i^{\mathrm{b}}} = \frac{p^{\mathrm{n}} - p^{\mathrm{mb}}}{\left|p^{\mathrm{n}} - p^{\mathrm{mb}}\right|}\,. \qquad (4)$$

(4)

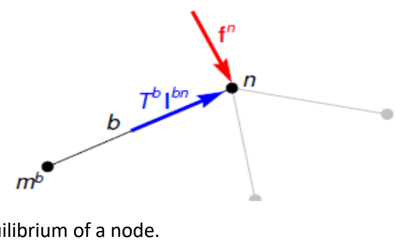


Figure 13. Equilibrium of a node.

The application of the TNA method was, therefore, first applied to a single transverse vault of the roof and then extended to the static and structural verification of all the other vaulted wall coverings of the church of Santa Maria della Libera, using as input datasets the point clouds already obtained from previous surveys.

It is worth pointing out that the virtual models obtained from the high-precision laser scanning tools have limitations from a computational point of view: in fact, they can be processed with computational software only after the point clouds have been transformed into polygonal surface models. In fact, structural analysis software uses an algorithm that requires as input data the geometric dimensions of the masonry object, which is usually never perfectly regular and homogeneous: these are historical masonry by their nature irregular, with uneven surfaces and consisting of ashlars that are not perfectly squared. The x, y, z spatial coordinates of the points surveyed using TLS and exported to Excel tables and .txt lists thanks to the "Cloud Compare" software must therefore be smoothed to obtain more regular surfaces, i.e. surfaces without folds, holes or overlaps.

To solve this problem and obtain coordinates that can provide correct geometric data to run the structural algorithm, an interpolating function described by the following polynomial formula was constructed in the case study of the Chiesa di S. Maria della Libera:

$$y = -0.0236\,x^6 + 0.023\,x^5 + 0.0677\,x^4 - 0.0597\,x^3 - 0.3024\,x^2 + 0.1172\,x + 12.871\,. \quad (5)$$

This made it possible to apply the TNA method to each of the cross vaults of the church roof under analysis and calculate the distribution of thrusts, as highlighted in Figure 14.

In this way it was possible to calculate, as it can be seen from Figure 15 and Figure 16, the maximum and minimum values of the thrust of each of the 389 branches of each cross vault and the corresponding minimum and maximum values of the height of each of the 222 nodes of the vault associated with the minimum and maximum thrust values. The experimental results showed that the maximum network node height characterizing the deepest boundary configuration, that is, the one associated with the minimum thrust, is 2.48 meters, while the shallowest boundary configuration, associated with the maximum thrust, has a value of 1.38 meters as the minimum node height.

3.2. Porta di San Lorenzo and Arco di Marco Antonio: GPS and photogrammetric surveying

From late Roman times the city was at the centre of a process of ruralisation that has become progressively more manifest in our days: from Roman, then Lombard, medieval city to transforming into a modern city. It is very likely that remains of the Roman city are preserved in the core of the medieval city: in fact, it is precisely the Porta San Lorenzo or Porta Capuana, believed to be of Roman origin, later recognized to be of medieval age, that marks one of the intermediate steps in the passage of the civic centre from one side of the valley "Pentime". Once passed the Pentime valley, it is possible to reach the medieval Church of the Madonna della Libera with the adjacent Marco Antonio's Arch and not far away Porta San Lorenzo, or Porta Capuana. Marco Antonio's Arch, located on the North-Western side of the S. Maria della Libera Church, wasn't sited in an appropriate position and easily accessible from all sides for a complete and accurate survey; for this reason, it has been object only of a georeferencing and a photogrammetric survey in relation on the front elevation of the arch. A GPS RTK survey and a 3D modelling by a TLS survey of the historical artefact have been carried out. The setting up of markers, used also as control points in the GPS surveying, allowed us to appreciate the accuracy of the point cloud created through the alignment process of photogrammetric images and the elaboration of the dense points cloud. Geometry, positioning and dimensions of the Roman round arch are comparable with the image of the artefact of the historical archive of the German Archaeological Institute in Rome. The historical image, probably unique, is dated at the early 1900s and now it is preserved in the National Photo Library of the German Institute (Figure 17).

In addition to these geomatic surveys, at a later stage a GPS survey was also carried out regarding the San Lorenzo Porta [36], [45] and a significant portion of the ancient Via Latina (Figure 18), the outcomes of which were reported within the GIS platform, previously implemented with all the collected datasets.

In addition to the GNSS survey, Porta San Lorenzo was also measured by a photogrammetric survey carried out through a Canon PowerShot SX720 HS camera with a CMOS sensor and 20.3 Mpx resolution. 200 images were taken to obtain a degree of overlap of at least 70 % in the longitudinal direction and 30 % in the transverse direction.

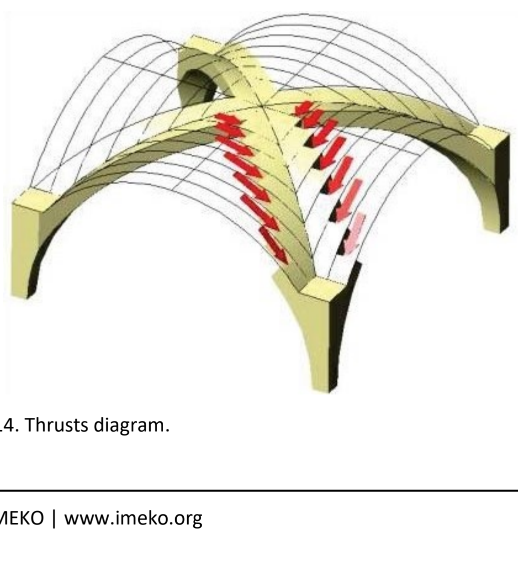


Figure 14. Thrusts diagram.

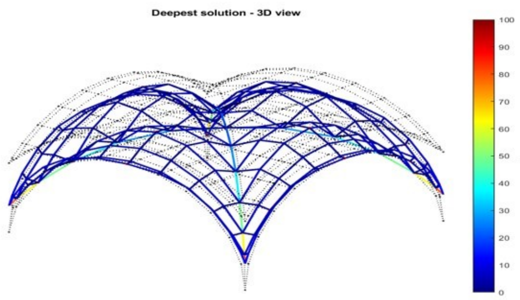


Figure 15. Distribution of the maximum thrusts.

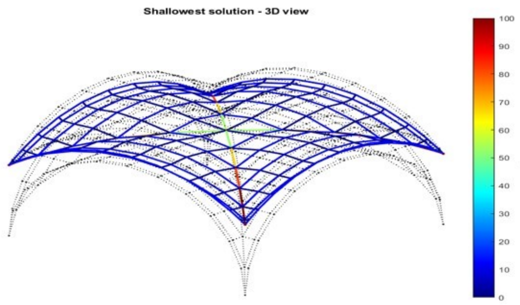


Figure 16. Distribution of minimum thrust.

Figure 17. Arch of Marco Antonio: photograph taken in the early 1900s by the Germanic Archaeological Institute in Rome (a); 3D model from the elaboration with image-based technique of the photogrammetric survey data (b).

Through the processing of the digital images, a dense point cloud was constructed with a linear mean square deviation value around 5 mm, from which a final textured model was finally derived using the Agisoft Photoscan software (Figure 19).

3.3. Close-range photogrammetry

The geomatic acquisition campaign at San Pietro Vetere Plateau that began in September 2015 was developed in parallel with the progress stages of the archaeological excavations, conducted near the remains of the ancient medieval basilica of S. Maria degli Angeli, a complex not yet entirely unearthed except for some perimeter walls over 3.00 meters in height, which were also the subject of topographic survey, as shown by the spatial framing scheme shown in Figure 20.

The plano-altimetric surveys were carried out with high-precision topographic instruments: a total station, characterized by an accuracy of 2 mm in measuring distances and 0.3 milli gon for angular measurements, and two GNSS geodetic receivers, Hiper PRO type, which were used in RTK (Real Time Kinematics) mode. The geomatics survey with ST GTP was carried out by employing three station points S100, S200 and S300 with local reference in station S100, and taking advantage of the classical triangulation scheme for local reference networks; conversely, the use of GNSS receivers made it possible to establish a global reference frame and, therefore, to enter the data not only in a map, as shown in Figure 19, but also in a GIS system.

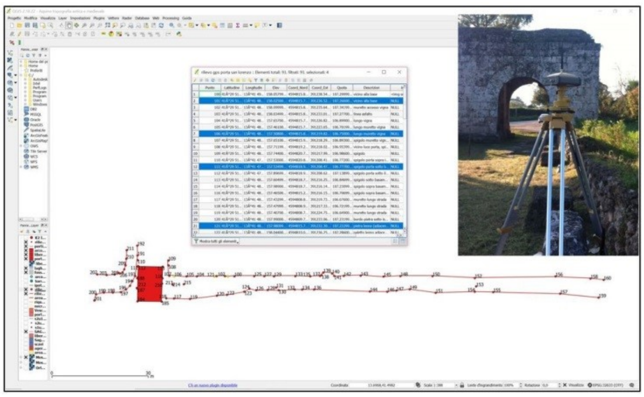


Figure 18. GIS screenshot relative to the GPS survey of Porta San Lorenzo and a portion of Via Latina, with the detail of the measurement booklet and image.

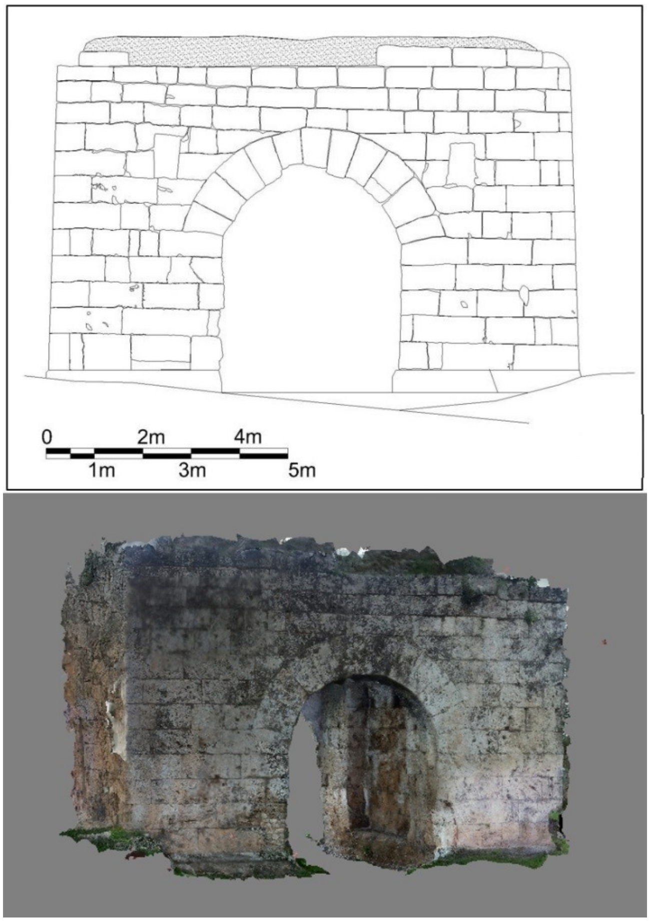


Figure 19. Prospect of Porta San Lorenzo obtained by overlapping with an ortho-mosaic extrapolated from 3D model (above); 3D model relative to Porta San Lorenzo (below).

The use of GIS software made it possible to integrate and enrich the typology of technical documents associated with the site's framing by overlaying multiple raster maps and inserting georeferenced vector elements into the map based on the surveyed coordinates. Specifically, two pilot areas of archaeological investigation were identified, which were excavated and surveyed in detail as highlighted in Figure 21.

Each measured point, in fact, was marked by an identification code (ID) where the elevation value and a brief description were associated with (see tables in Figure 21) the planimetric georeferencing ensured by the coordinate values of the observations, compensated and reported in the measurement booklet. The two excavation sites, with planimetric dimensions between about 4.00 and 6.00 meters, were deepened to an elevation of about 1.00 meter and led to the discovery of interesting archaeological evidence: in nr. 1, fragments of colourfully decorated flooring with geometric patterns (probably

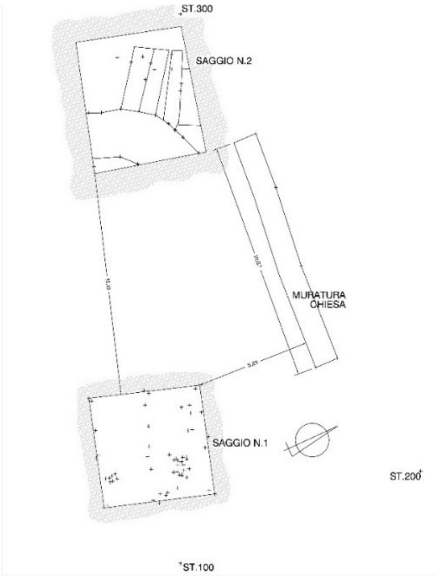


Figure 20. Planimetric view of the archaeological excavation.

made for the church in the 12th century) as well as some women's jewels were found; in nr. 2, on the other hand, nr. 4 tombs were unearthed, the burial site of human figures whose skulls, bone fragments of lower limbs and other remains were found.

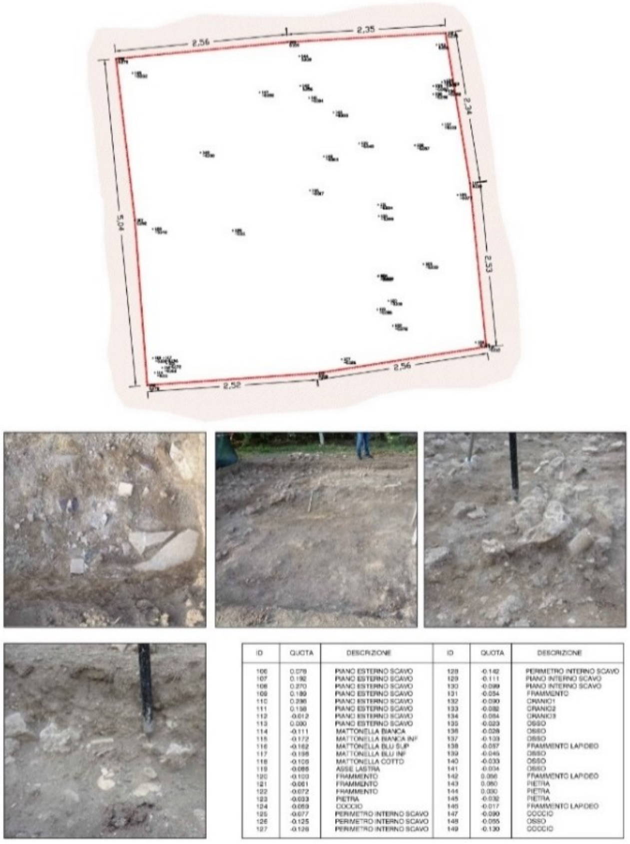
Regarding the first excavation, a portion of the pavement revealed the presence of a first pavement phase datable to the beginning of the 12th century on which, subsequently, a second pavement, also of mosaic form, was laid. The latter, in turn, can be attributed to the same artistic movements corresponding to four generations of marble-workers active in the city of Rome around the 12th and 13th centuries and known as Cosmati; for this reason, such pavements, also present and still visible in the well-preserved pavement of the Abbey of Montecassino, are called Cosmateschi.

Besides the photographic documentation acquired as evidence of the excavations, accurate close-range photogrammetric measurements, combined with the subsequent processing of 3D models, enabled detailed surveys of these finds.

Specifically, the photogrammetric restitution of a fragment of the pavement was obtained by processing three images, one nadiral and two laterals, obtained with a digital-backed IMACON photogrammetric camera at 30 centimetres [2], [4], [6]. With reference to the digital image processing data, three photogrammetric shots were simultaneously processed, reported in the same reference system, to obtain an overlap of about 60 %. This allowed the corresponding homologous points in the images to be identified, any distortion errors to be corrected, and the 3D coordinates of the detected points to be obtained. Three rectified images of the mosaics were processed in the so-called "waterline" technique; this has the advantage of generating each mosaic tile as a single entity, which allows them to be composed through rotation and grafted in the most appropriate way.

A faithful reproduction of the mosaic is also possible with this technique, thanks to an automatic reproduction of the modules, called "cloning" by experts. The mosaic found in the N-E sector consists of tesserae of different shapes: fusiform (length 10 cm, maximum width:3.3-3.7 cm, thickness:1.3-1.9 cm); quadrangular (side 4 cm, thickness 1.9 cm); triangular (equilateral triangles with sides between 2-3.5 centimetres, thickness 0.5-2 cm). The materials used are different: the spindles are fine-grained white marble; the squares are yellow and white ancient marble; the triangles, on the other hand, show the use of coloured marbles such as porphyry, serpentine and white marble. The motif appears as a circle of four castings with an inscribed square with concave sides; it shows inside a motif formed by a central square tile on each side of which four equilateral triangles are arranged.

The images in Figure 22 show the successive stages of "in situ" discovery of mosaic fragments, their reassembly, and the results of stereoscopic photogrammetric restitution. This decorative scheme finds analogies in an area of direct Cassino



ID	QUOTA	DESCRIZIONE	ID	QUOTA	DESCRIZIONE
106	0.078	PIANO ESTERNO SCAVO	128	-0.142	PERIMETRO INTERNO SCAVO
107	0.192	PIANO ESTERNO SCAVO	129	-0.111	PIANO INTERNO SCAVO
108	0.270	PIANO ESTERNO SCAVO	130	-0.099	PIANO INTERNO SCAVO
109	0.189	PIANO ESTERNO SCAVO	131	-0.054	FRAMMENTO
110	0.236	PIANO ESTERNO SCAVO	132	-0.090	CRANIO1
111	0.158	PIANO ESTERNO SCAVO	133	-0.082	CRANIO2
112	-0.012	PIANO ESTERNO SCAVO	134	-0.084	CRANIO3
113	0.000	PIANO ESTERNO SCAVO	135	-0.023	OSSO
114	-0.111	MATTONELLA BIANCA	136	-0.028	OSSO
115	-0.172	MATTONELLA BIANCA INF	137	-0.133	OSSO
116	-0.162	MATTONELLA BLU SUP	138	-0.057	FRAMMENTO LAPIDEO
117	-0.198	MATTONELLA BLU INF	139	-0.046	OSSO
118	-0.106	MATTONELLA COTTO	140	-0.033	OSSO
119	-0.086	ASSE LASTRA	141	-0.034	OSSO
120	-0.100	FRAMMENTO	142	0.056	FRAMMENTO LAPIDEO
121	-0.061	FRAMMENTO	143	0.060	PIETRA
122	-0.072	FRAMMENTO	144	0.030	PIETRA
123	-0.033	PIETRA	145	-0.032	PIETRA
124	-0.069	COCCIO	146	-0.017	FRAMMENTO LAPIDEO
125	-0.077	PERIMETRO INTERNO SCAVO	147	-0.090	COCCIO
126	-0.125	PERIMETRO INTERNO SCAVO	148	-0.055	OSSO
127	-0.126	PERIMETRO INTERNO SCAVO	149	-0.130	COCCIO

Figure 21. Survey tables: photographs, identification codes, elevation values and short description.

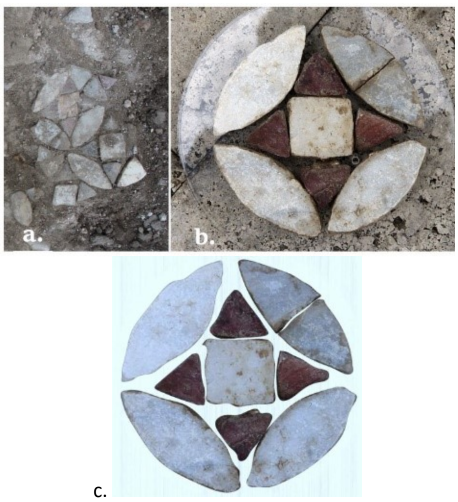


Figure 22. a) Mosaic fragment found "in situ"; b) Re-composition of the geometrical pattern aimed at a close–range photogrammetric restitution; c) Digitalization and photogrammetric restitution with the "waterline" technique.

influence, in the church of S. Maria Maggiore erected in the municipality of S. Elia Fiumerapido in the province of Frosinone. Considering stylistic comparisons and excavation data, the floor mosaics can be dated to the first half of the 12th century.

In the second archaeological site, the excavation recovered a portion of the perimeter walls of a building older than the church ruins visible on the surface and, apparently, completely disconnected from them. This structure consists of a base row of large, squared blocks on which a masonry of stones, brick scraps and mortar was erected. Four so-called "*cista*" burials are grafted onto this masonry, two of which are characterized by single inhumations and the other two by twin inhumations (Figure 23 and Figure 24).

All feature a box made of lithic blocks. Although the covering blocks of the quadrangular box were partially removed and/or destroyed, probably because of desecration and/or looting in different eras, some coins, small rings, and vitrified pottery fragments were found in the field around the coffins, which provided useful information for dating the human remains, probably belonging to the medieval age.

Digital and analogical techniques were used to determine the volumes and dimensions of some human remains represented by a skull and bone fragments.

The cameras used for filming, a calibrated full frame Pentax K1 and a Hassemblad X1D, equipped with a large sensor, used the very innovative "pixel shift" technology. "Pixel shift resolution" captures four images of the same scene by mechanically and automatically shifting the sensor by a single pixel, for each image taken, resulting in a single image characterized by almost absolute colour verisimilitude [35].

For filming, an ad hoc laboratory-made support device was constructed, consisting of a set of mechanical joints that allowed the skull to be suspended.

Figure 23. Archaeological digs of tumbs *a cista*.

Figure 24. Human bones.

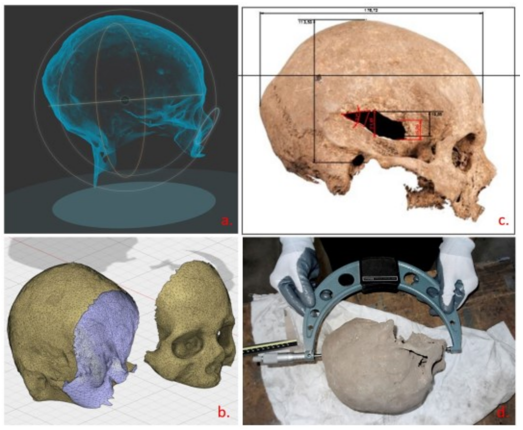


Figure 25. a) Digital model of a skull with orbital plane; b) Digital skull decomposition; c) Analogical longitudinal and transversal measurements and determination of the lacking part due to a wide fracture; d) Micro-mechanical measurements.

The use of a rotating plate, which was necessary for constant and uniform illumination of the object under a controlled intensity, shielded, bidirectional light of 6000 Kelvin, allowed the photogrammetric shots to be taken every 10 degrees for a total of 36 images.

The choice of bidirectional light, fed by two sources placed on tripods and tilted 45 degrees to the foreground of the specimen, was necessary for uniform, shadow-free illumination. For greater measurement accuracy (reprojection error of 1.01 pixel), 25 markers were applied, thus avoiding digital artefacts containing holes in the mesh of the three-dimensional model. The surface area and volume of the skull were also measured from inside the specimen, making it possible to measure thickness at every point. A sharp and wide fracture is also evident, due to traumatic injury with breakthrough of the parietal lobe, having length of about 14 centimetres and width varying from one hundredth of a millimetre to one millimetre. Measurements made via software and exported in .dxf format were based on 2 control points for objective comparison with an analogue microscale measurement. The values of the digital measurements were verified by micro-mechanical comparison measurements made in a specialized laboratory using micrometres and centesimal analogue gauges (Figure 25).

Excellent measurement values were also obtained with respect to the longitudinal plane, with precise correspondences between digital and analogue values, which allowed quantification of an orbital cavity breakthrough of an area of about 6 square centimetres.

It should be emphasized that recent technological progress has narrowed the gap between experts and amateurs, if the accuracy of measurements is preserved. This aspect can be declined not only for acquisition devices but also for the realization of final products: in terms of acquiring and processing data in an economical and transferable way, modern photogrammetric systems are particularly attractive to produce 3D models, with the availability of 3D visualization and solid printing. This was also evident in the 3D modelling of another artefact found in excavation operations: as seen in Figure 26. As in the case of the skull, through target affixing it was possible to determine the exact geometry of a human mandible and its 3D reconstruction in 6 orbital planes.

Regarding the excavations and all the unearthed findings, two interactive web maps were created, one for each stratigraphic

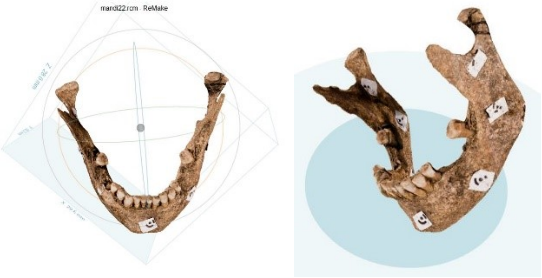


Figure 26. 3D reconstruction of a human mandible.

unit, easily exportable in .html format thanks to the QGis2web plug-in. In each screen of the information system, it is possible to interact with the map in different ways to understand both the location of the study area and the descriptive elements of the findings, such as: the identification number and the plano-altimetric coordinates of the surveyed points, the description of the findings, the illustration of the images associated with the object or area of reference, according to a synthetic representation of the elements belonging to the excavation dataset. It is possible, through queries, to select for each find information such as date, material, type, photos.

Finally, the preparation of 3D digital models represents the optimal methodology to preserve the excavation memory. The processing of the DSM, obtained using ArcGIS software, related to the two stratigraphic units for each excavation, was carried out starting from the coordinates of the points surveyed, both in plan and along the boundary of each excavation, by a total station. The extrusion of the findings associated with the first and second stratigraphic units, respectively, is shown in different colours in Figure 27; the points surveyed from a total station and the projection of the excavation boundary are also shown [42], [46], [47], [48], [49], [50], [51].

4. CONCLUSIONS

The methodological-operational approach applied in the research activities on the archaeological evidence of the city of Aquino highlights the fundamental contribution that the technological innovations of geomatics can provide for the construction of an "intelligent" and articulated knowledge concerning the cultural heritage.

It is a multi-scalar knowledge base in which the geometric data obtained from the different metric, topographic and photogrammetric surveying techniques (total station, GNSS systems, terrestrial laser-scanning, digital photogrammetry) are not only integrated with other information datasets (historical-archaeological data) to produce digital information models (BIMs) and interactive GIS platforms that can be easily consulted by different stakeholders, but can also be the base for the elaboration of more complex and detailed cognitive analyses, such as TNA structural analysis, for the definition of conservation and enhancement interventions.

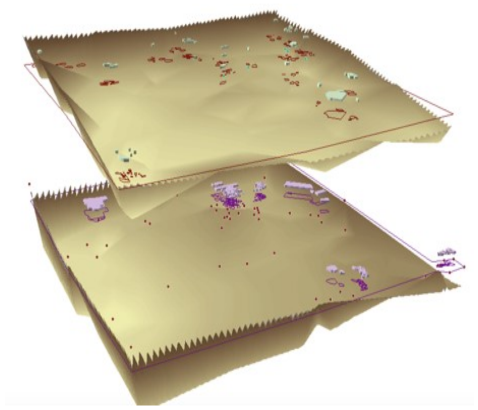


Figure 27. DSM of two stratigraphic units relative to the first excavation; the extrusion of the findings associated with the first and the second stratigraphic units are represented in the colours light green and purple respectively (3.).

Specifically, the HBIM digital model of the Church of Santa Maria della Libera, for example, is configured as a "container model" that represents the connective element between different disciplines and fields of research, including, just as required by BIM technology, both a geometric database and information of different nature (characteristics of materials, state of preservation and level of structural safety of the vaulted elements). In addition to this, the high-precision 3D models developed from detailed photogrammetric measurements of archaeological fragments and human remains found in the excavation areas constitute an interesting "final visual product" that is immediately understandable even for non-experts, and thus particularly useful for wide-ranging knowledge dissemination. Similarly, interactive web maps concerning archaeological prospecting highlight how the broad potential of GIS as a tool for sharing and unifying metrically, typologically, and temporally heterogeneous data can be exploited with the aim of transferring spatial observations to the historical-archaeological interpretation of sites.

These are, therefore, digital models and platforms in which interdisciplinary databases converge, which, thanks to modern geomatics monitoring techniques, can be implemented almost in real time, thus representing a constantly updated information base on which both future safeguarding, enhancement and programmed maintenance interventions and an increasingly broad dissemination of knowledge can be set as an educational tool to raise community awareness about the multiple potentialities inherent in the cultural heritage that surrounds us. This also implies an important collaboration between universities, research centres, superintendencies, public and private institutions for the enhancement and dissemination of Cultural Heritage to a mass audience, thus fostering interesting development opportunities.

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