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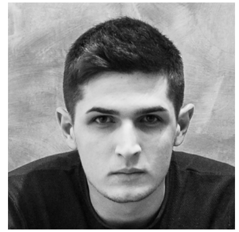
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Integrated 3D methodologies for the survey of archeological heritage

The research deals with the topic of archaeological surveys through the use of laser scanners and drones and the integration of appropriate data processing methodologies, aimed at promoting processes of documentation, knowledge, restoration and enhancement of the archaeological heritage.
The object of the investigation is the Mausoleum of Sant'Urbano at the 4th mile of the Via Appia Antica, dating back to the 4th century AD, annexed to the Appia Antica Archaeological Park in 2021. Prior to 2021 it was privately owned and had undergone disfigurements and alterations of the original masonry.
The research presented derives from a scientific collaboration agreement between the Appia Antica Archaeological Park, the Department of Architecture at Roma Tre University, the Department of Humanities, Philosophical Studies, and History of Art at Tor Vergata University, aimed at study, survey and monumental analysis of the mausoleum.
The presented research resulted in the definition of a survey methodology of the archaeological heritage in which the data acquisitions from the aerial photogrammetric method and from the instrumental method are integrated aimed at the documentation, knowledge and dimensional and morphological restitution of an asset of significant historical and identity interest. The first results have made it possible to obtain a graphic restitution, numerical models or orthophotos on the basis of which the archaeological and historical multidisciplinary studies, the restoration and conservation interventions and the enhancement and use strategies by the Appia Antica Archaeological Park will be conducted.

Keywords:
UAV; SAPR; laser scanner; survey; archaeological heritage

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1. INTRODUCTION

The research deals with the topic of archaeological surveys through the use of laser scanners and drones and the integration of appropriate data processing methodologies, aimed at promoting processes of documentation, knowledge, restoration and enhancement of the archaeological heritage.
The object of the investigation is the Mausoleum of Sant'Urbano at the 4th mile of the Via Appia Antica, dating back to the 4th century AD, annexed to the Appia Antica Archaeological Park in 2021. Prior to 2021 it was privately owned and had undergone disfigurements and alterations of the original masonry [1]. For these reasons, the public institution needed a comprehensive survey campaign to document the current state (both metrically and materially) of the acquired asset in order to initiate all necessary operations for understanding the structure and the site (figs. 1-2).
The research presented derives from a scientific collaboration agreement between the Appia Antica Archaeological Park, the Department of Architecture of the Roma Tre University, and the Department of Humanities, Philosophical Studies, and History of Art at the Tor Vergata University, aimed at study, survey and monumental analysis of the mausoleum [2].
The research has general objectives and specific objectives. The general objectives include: i) defining a methodological direction that integrates survey data obtained from laser scanners and data obtained from UAVs (Unmanned Aerial Vehicles) up to the vector graphics restitution; ii) obtain a survey of the mausoleum and of the site, previously never investigated, with a CAD restitution in 1:50 scale aimed at multidisciplinary investigations; iii) promote archaeological investigations to study the unknown aspects of the architecture and the area.
The specific objectives concern: i) discovering the archaeological portion; ii) analyze the paving section of the road that connects the mausoleum to the Via Appia Antica; iii) favor investigations on the topographical and urban relationship between the mausoleum and the Via Appia Antica; iv) analyze the close mix, also through choices of representation, between archeology and landscape that is vivid in this area of the Parco dell'Appia Antica; v) start future processes of restoration, enhancement and public use of the property.

2. METODOLOGY

The survey methodology involved an initial data acquisition phase conducted by placing markers on the ground and within the mausoleum, and then scanning with a Z+F IMAGER 5010X laser scanner (MicroGeo) using 48 stations positioned throughout the site, the mausoleum, and the corresponding section of Via Appia Antica. To ensure completeness of the model in inaccessible and elevated areas, terrestrial laser scanner surveys were supplemented with data acquisition using a DJI Matrice 210 V2 UAV equipped with a Zenmuse

Fig. 1 - View of the Mausoleum of Sant'Urbano on Via Appia Antica in Rome, around 1910 (Archivi Alinari, Florence).

Fig. 2 - The Mausoleum of Sant'Urbano at the fourth mile of Via Appia Antica in Rome (photos by the authors, September 2022).

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X5S camera.

2.1 DATA ACQUISITION AND PROCESSING FROM DRONE

The UAV DJI Matrice 210 V2 acquisition phase was conducted following a flight campaign at a height of 25 meters, which was designed during the survey campaign planning for the entire intervention area [3] (Fig. 3). In addition, close-range and detailed flights were carried out over the entire archaeological mausoleum to obtain a highly characterized mesh model with high-resolution textures [4]. This second phase was necessary for the drone survey to address significant blind areas caused by the presence of tall trees, from the Pinus pinea and Cupressus sempervirens families, with consistent foliage obstructing the recording [5]. The flight conducted above the dense vegetation was supplemented with flights beneath, around, and inside the Sant'Urbano mausoleum.
To ensure accurate and calibrated data overlap for subsequent processing, marker points were strategically positioned during the survey campaign. These markers facilitated easy identification of key points on the three Cartesian planes and helped in aligning the data.
The images acquired by the drone were processed using Structure from Motion (SfM) procedures, characteristic of Reality-Based reconstruction processes, which initially allowed obtaining a dense point cloud and then the orthophotos of the site, necessary for the two-dimensional CAD representation (Fig. 4).
The first model obtained from the processing of the drone-acquired data was a dense point cloud only of the Sant'Urbano mausoleum, exported in e57 format, with a level of detail exceeding seventy million points, which had to be integrated with the laser scanner data.
Subsequently, two mesh models with high-resolution textures were created. The first one represents the entire surveyed area, including trees and foliage, with the necessary approximations due to the issues in reproducing leaf masses and moving canopies during the capture phase. Photogrammetric rules, which link multiple photographs based on corresponding characteristic points (automatically recognized by the software), rarely work for vegetation reconstruction, as this one moves under the influence of even minor winds.
The second mesh model, with nearly four times higher resolution than the first, focuses specifically on the mausoleum and its immediate context.

Fig. 4. Orthophoto obtained from drone acquisition and processed using SfM procedures (processing by the authors).

Fig. 3. Acquisition of the Mausoleum of Sant'Urbano using a DJI Matrice 210 V2 UAV with a Zenmuse X5S camera (photo by the authors, September 2022).

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From this model, detailed orthophotos were generated to be used as a graphical basis for defining homogeneous areas and mapping materials.
The two files (the point cloud and the detailed mesh) underwent various management and verification procedures. The point cloud was aligned (with an automatic spatial rototranslation) with the one created by the laser scanner using the markers placed during the capture phase, achieving an optimal collimation with a marginal error of 2mm.
The mesh model, having the same orientation as the point cloud, was manually rotated and translated by assigning the coordinates of the markers according to a Cartesian origin in the three-dimensional space. This alignment error likely resulted from the lower precision of the drone's GPS compared to the surveying with a total station using markers in the real space [6].

2.2 DATA ACQUISITION AND PROCESSING FROM LASER SCANNER

The laser scanner survey campaign lasted 5 days, during which 48 high-resolution scans were made, covering the entire site and aiming at avoiding blind areas caused by vegetation [7]. The site is characterized by the presence of pine trees, invasive spontaneous vegetation, variations in terrain elevation hosting trees and shrubs, and a stretch of basalt pavement connecting the mausoleum to Via Appia Antica. The scans were distributed as follows: 20 for the interior and exterior of the mausoleum, 3 along the basalt road connecting the mausoleum Via Appia Antica, 20 in the garden area, and 5 along Via Appia Antica itself. It's important to note that the client requested a survey not only of the mausoleum of Sant'Urbano but also of the entire context, including the position of trees within the site and the representation of the entire vegetation as an integral part of the mausoleum's context, as it is located within a highly protected area like the Parco dell'Appia Antica.
Therefore, the selection of scan positions was carefully planned on paper (with the help of pho-

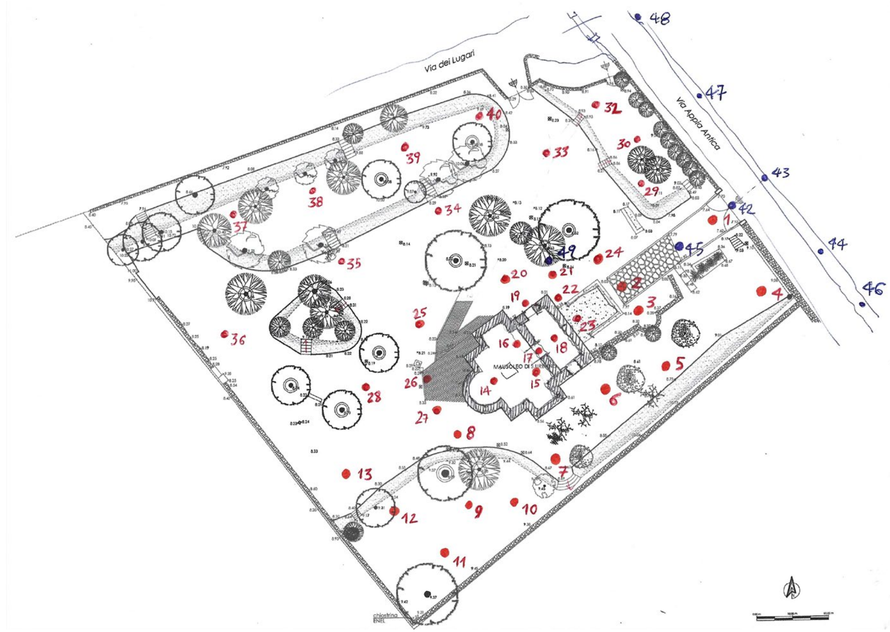

Fig. 5 - Plan of the laser scanner acquisition stations (graphic elaboration by the authors based on a survey from the early 2000s provided by the Parco Archeologico dell'Appia Antica).

Fig. 6 - Acquisition of the Mausoleum of Sant'Urbano using a Z+F IMAGER 5010X laser scanner (MicroGeo) (photos by the authors, September 2022).

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tographic documentation) to capture both the archaeological structure and the complex vegetation and terraced layout of the entire site (Figs. 5-6). The different scan positions were aligned in Recap Pro, ensuring a perfect overlapping between the individual point clouds, resulting in a single file.
The second phase involved processing the data obtained from the laser scanner and drone using multiple alignment and virtual reconstruction methodologies, as well as the intersection of data obtained through alignment and collimation software. The point cloud obtained from the laser scanner was aligned with the point cloud obtained from the drone to complete the model in its elevated or hidden parts which were not visible from the ground. The final file generated from this process served as the basis to re-draw the characteristic sections of the mausoleum and the orographic line of the complex in a CAD (figs. 7-8).
From a representation outlook, the obtained point cloud provides an evocative image of the vegetation, as experienced in other cases [8]. Therefore, it was decided to present the entire complex using a mixed representation approach, where the greenery is rendered through the point cloud, providing a more artistic representation (almost like a digital watercolor), while the architectural aspect is captured through orthophotos of the mesh model (aligned with the same section planes). The former delivers a more artistic representation, while the latter provides a material-based image, presenting the surface details of the mausoleum and various wall configurations (different types of bricks, blocks, plaster, as well as collapses and gaps) [9].

Fig. 7 - Screenshot of the point cloud of the site: on the front, Via Appia Antica (graphic elaboration by the authors).

2.3 ORTHOPHOTOS ELABORATION

Finally, the corresponding orthophotos were generated for the sections and plans conceived for the 2D graphical representation, using two different processes. First, using to a basic floor plan, clipping planes were positioned for the sections to be constructed both in the CAD and on the mesh model of the mausoleum. A significant attention was given to accurately placing the planes in both software environments to ensure an optimal alignment of the two orthophotos created for each reference section.
The orthophoto related to the vegetation was directly produced in CAD by appropriately scaling the point cloud (scale 1:50) and generating PDF files showing the entire site, sectioned on the chosen plane, displaying the botanical and chromatic variety of the context alongside the visualization of the architectural structure.
On the other hand, the isolated orthophoto of the mausoleum was produced from the mesh model using Rhinoceros software, directly printing, with the same scale, the high-resolution textured render of the model with maps created by the reality-based software.
The two images obtained from these different processes were subsequently processed to create the final backgrounds for the CAD drawings: one orthophoto with full opacity of both sources and another with 60% opacity for the vegetation to emphasize the focus on the archaeological monument and its 2D graphical representation.
However, the choice (made afterwards) to create a collage of different orthophotos and allocate the architectural representation to a material-based approach, derived from the textured mesh model, resulted in a new issue which needed to be resolved. The archaeological complex has two enclosed rooms: one located beneath the ramp-staircase of the main facade and the other, a barrel-vaulted corridor providing access to the interior of the mausoleum itself. These two areas were not surveyed during the drone campaign due to the impossibility of accessing and flying in narrow spaces.
A second site visit was required for a photogram-

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Fig. 8 - Screenshot of the point cloud of the site: the main facade (graphic elaboration by the authors).

metric survey in order to complete the orthophotos for the missing parts of the sections which cut through those rooms. The photography campaign for the photogrammetric reconstruction involved capturing 494 photos for the vaulted room, divided into 3 spherical compositions, 8 semi-spherical compositions close to the walls, and a set of photos with parallel axes of the four sides of the room for a perfect reconstruction of textures. For the space beneath the ramp, 307 shots were taken, divided into a central spherical composition and 8 semi-spherical compositions at the edges and against the walls.
All photos were taken manually, setting the exposure time and aperture consistently across all photos to achieve uniformity in terms of light and shadow areas. The color balance was initially set by photographing a white sheet inside the space (each one with different lighting conditions) and adjusting the white balance of the subsequent photo set to match the white of the sheet captured by the camera. Additionally, post-production of the images was necessary to work on heavily shaded areas that needed recovery and reduce the brightness of overexposed areas. This process was facilitated by shooting in RAW format, which allows greater post-production versatility across different channels.
The reality-based software successfully reconstructed the virtual space in its entirety, except for the glass areas, whose reflections are common issues in digital reconstruction.
The recreated models, one for each room, were exported as high-resolution textured meshes, opened in Rhinoceros, positioned, subjected to clipping planes, and rendered the same way as the rest of mausoleum. The renders were then placed inside the orthophotos to complete the material representation of the architectural envelope [10].

3. 2D GRAPHICAL REPRESENTATION

The third phase focused on the 2D vector representation of the site and the mausoleum at a scale of 1:50. This was achieved by importing the

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point cloud and the orthophotos into a CAD environment to produce two plans at different heights and ten elevations. The point cloud was sectioned using section planes to facilitate the creation of floor plans, cross-sections and elevations [11].
The graphical representation of the site highlights an area (approximately 70 meters x 70 meters on the longer sides) accessible by two entrances on Via dei Lugari and one entrance on Via Appia Antica. The mausoleum occupies the southeastern part, while the remaining portion features a garden with landscaped "islands" at an elevation of approximately +1.50 meters above ground level, with pine trees, some cypress trees, and shrubs.
The representation highlights the typological, metric, and spatial characteristics of the architectural structure. The current state of the mausoleum is characterized by a nearly square central-plan space with two side niches and an axis-aligned apse. However, the roof and the floor of the upper level are missing. The space is accessible through a barrel-vaulted room where the current entrances are located. Additionally, there is a room located beneath the substructure that once supported the staircase leading to the main entrance of the mausoleum. Adjacent to this room and measuring approximately 10 meters in length and 4 meters in width, a stretch of intact basalt pavement can still be seen, along with some paving stones near the entrance on Via Appia Antica. The connecting path from the mausoleum to Via Appia Antica is approximately 21 meters long. In the eastern sector of the site, a basin and a fragment of masonry with an apse were also surveyed (figs. 9-10).
The mausoleum itself has a length of 25 meters, a width of 15 meters, and a height of approximately 12 meters. The exterior elevation near the mausoleum is higher than the interior elevation, with a difference ranging between 17 and 90 centimeters.
The main interior space shows numerous defects, collapses, and damages. The wall housing the apse features a large upper opening with a semi-circular arch, while the opposite wall has an access point with a segmental arch, variations in wall surfaces, and the entrance (currently walled up) which once led to the upper room. The elevations show the construction technique, the type of masonry used, flat and relieving arches, variations in wall types, stone inserts, sections with plaster, and collapsed or missing portions.
Figure 11 is a longitudinal section that illustrates the sequence of spaces and the volumetric ar-

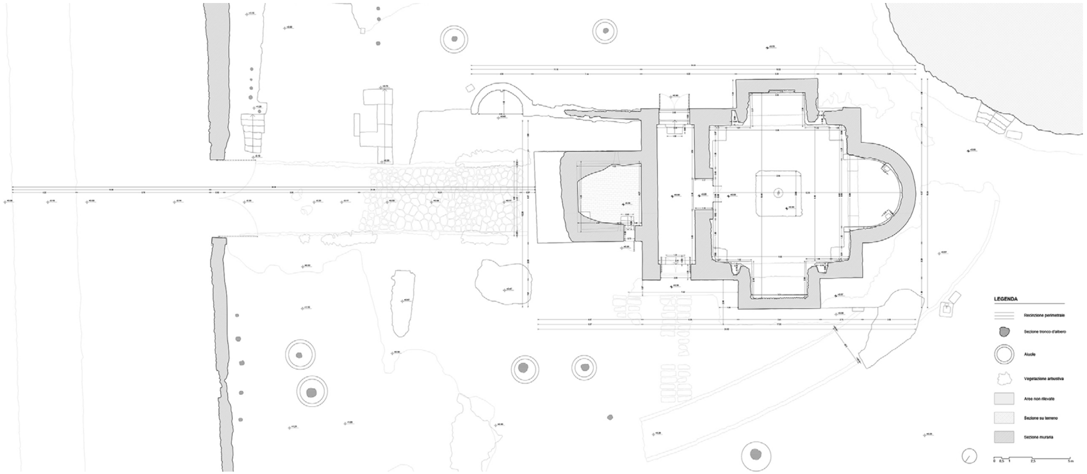

Fig. 9: Floor plan of the Mausoleum of Sant'Urbano (graphic elaboration by the authors).

Fig. 10. Floor plan of the Mausoleum of Sant'Urbano: integration of the CAD vector representation with the orthophoto (graphic elaboration by the authors).

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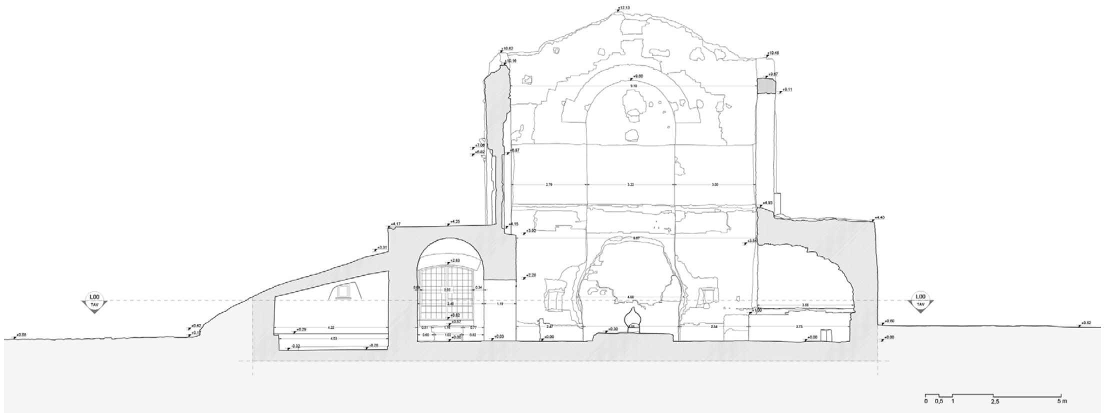

Fig. 11 - Longitudinal section CC': vector graphic representation in CAD (graphic elaboration by the authors).

Fig. 12 - Longitudinal section BB': integration of vector-based CAD drawing with orthophoto (graphic elaboration by the authors).

ticulation, including the room beneath the substructure that supported the staircase, the barrel-vaulted room, and the main interior space. In the central part, there is a 3-meter-wide niche that rises to 9 meters high, with the intermediate floor missing. The lower part highlights the lacks in the masonry, two small openings, and the apse. The upper part reveals the progression of the rear wall, the lack of a roof, and the 4-meter opening in the wall above the apse.
Figure 12 shows the opposite longitudinal section, created by integrating the vector-based CAD and the orthophoto. This representation showcases the material quality, the current state of the masonry, changes in wall types, and the extent of collapses and gaps. The orthophoto integrated with the vector-based CAD was obtained by combining the orthophoto of the mausoleum with a fill of 100% and the context orthophoto with a fill of 60%. This choice was made to convey both the material quality of the structure and the environmental quality of the surrounding context, while maintaining a visually lighter graphic for the landscape to emphasize the architectural object and provide depth to the representation.
Figure 14 highlights the main facade with the substructure in the foreground and the main interior space in the background, showcasing relieving arches and isolated stone elements in contrast to the brickwork. The graphic processing was achieved through vector-based restitution in CAD, incorporating the orthophoto and delineating the portions of different types of masonry (masonry, irregular masonry, uncertain masonry, cement work, blocks of tuff, individual stone elements).

4. REPRESENTATION AND INTERPRETATION

The representation of the survey results was conducted in four graphic variants to meet different needs: i) exclusively vector-based graphics; ii) vector-based graphics of the architecture integrated with orthophotos of the mausoleum (100% fill) and the context (60% fill); iii) vector-based graphics with delineation of portions indicating

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the type of masonry; iv) orthophotos.
This choice was motivated by the fact that orthophotos add a higher level of discretization and contribute to a better representation of the context (green areas, vegetation, pavements) and the mausoleum (material aspects, chromatic variations, decay) (fig.15). Therefore, it is important not only to integrate different representation modalities but also to have the possibility to conduct different types of data processing starting from a single three-dimensional numerical model (the point cloud). In fact, two types of processing were derived from the point cloud: i) vector-based floor plans, elevations, and sections; ii) raster orthophotos.
In this phase, great attention was given to the aspect of interpreting and discretizing the geometric data in order to achieve a correct representation and subsequent accurate reading of the architectural object in terms of typology, composition, form, space, materials, structure, and dimensions [12]. In an architectural subject predominantly characterized by exposed masonry which defines architectural space (thus lacking decorative elements), it is important to highlight variations in masonry types, structural elements, deficiencies, gaps, and isolated stone elements. This allows for a multidisciplinary understanding of the architecture by all the professionals involved in the study and enhancement of the asset (architects, archaeologists, historians, conservators) [13].
The material aspect was represented by drawing portions of areas characterized by the same masonry, using samples extracted from the orthophoto (fig. 16).
All the survey representations were developed to depict the site in its entirety. This approach allows for an understanding of the dimensional relationship between the architecture and the surrounding vegetation, the environmental qualities, the topographic variations of the terrain, and the archaeological level. For example, the longitudinal sections illustrate the mausoleum and the area up to the Via Appia Antica, providing a description of the relationship between the monument and its context, the archaeological level of the con-

Fig. 13 - Transverse section 44': integration of vector-based CAD drawing with orthophoto (graphic elaboration by the authors).

Fig. 14 - Transverse section 11': integration of vector-based CAD representation with orthophoto and masonry types (graphic elaboration by the authors).

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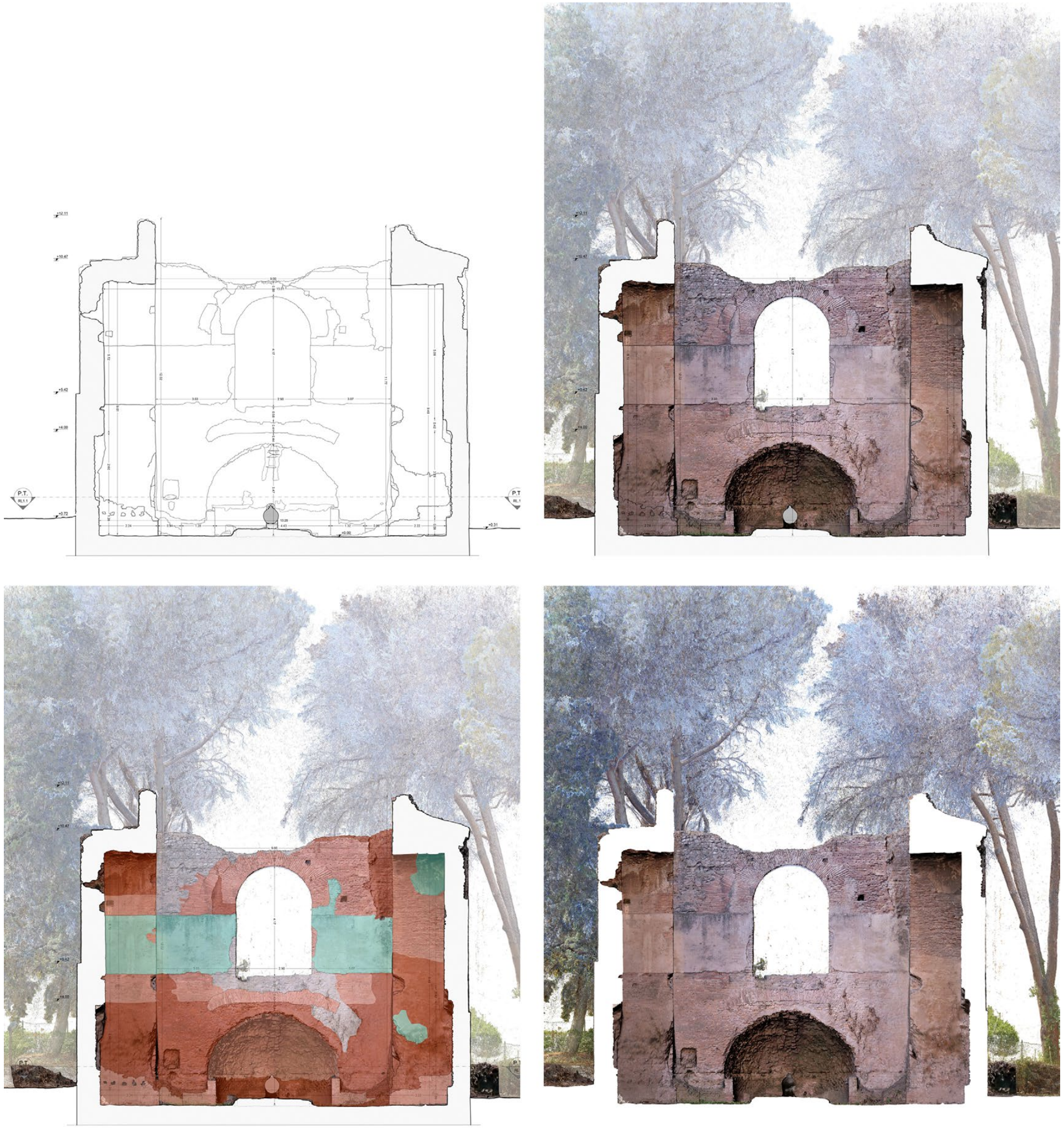
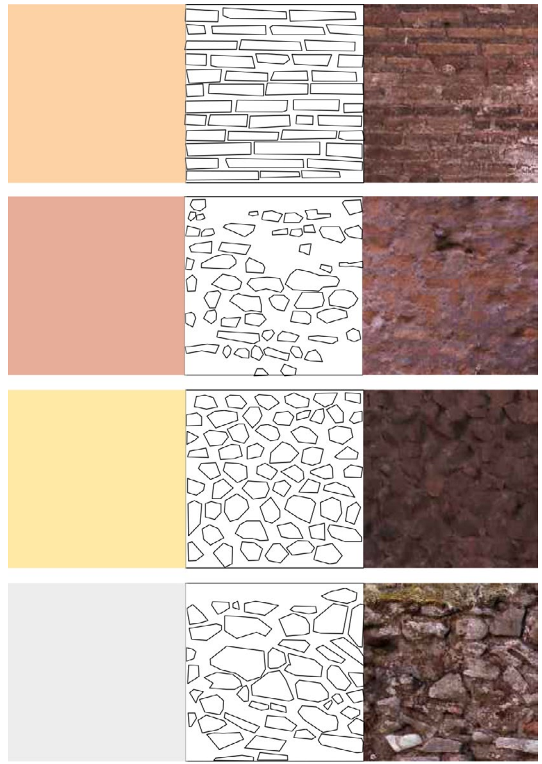


Fig. 15 - The four graphic variations of the survey results: a) Exclusively vector-based representations; b) Vector-based representations integrated with orthophotos of the mausoleum (100% fill) and the context (60% fill); c) Vector-based representations with the delineation of portions indicating the type of masonry; d) Orthophotos (graphic elaboration by the authors).

Fig. 16 - Samples of masonry found in the Mausoleum of Sant'Urbano: brickwork, cement work, irregular masonry, uncertain masonry (graphic elaboration by the authors).



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nection path between the mausoleum and the via Appia Antica, and the terrain profile. On the other hand, the transverse sections depict the mausoleum up to the entrance on via del Lugari, showing how the terrain profile changes according to the arrangement of terrain "island" containing trees and shrubs (figs. 17-18).

5. CONCLUSIONS

In recent years, all fields of knowledge have been influenced by technological and instrumental innovations, leading to new methodological procedures. These developments have also affected disciplines involved in the monitoring and understanding of cultural heritage. Thanks to these innovations, it is now possible to manage and coordinate the complexity of architectural and urban phenomena. This process of renewal involves both data acquisition methods and their management. Tools and methodologies are needed to create 2D and 3D models, aiming to facilitate analysis and valorization of cultural heritage. Therefore, all processes related to data acquisition, management, and representation that support the phases of documentation, understanding, and valorization of cultural heritage should be supported.

Fig. 17 - Longitudinal section BB' including the entire site up to Via dell'Appia Antica (graphic elaboration by the authors).

Fig. 18 - Transverse section 55': including the entire site (graphic elaboration by the authors).

The research results pertain to the development of a methodology for surveying archaeological heritage, integrating data acquired through aerial photogrammetry and instrumental methods for documenting and understanding a historically and culturally significant asset, and for its morphological and dimensional representation. This asset has not been fully investigated until now due to its private ownership and not belonging to the Parco Archeologico dell'Appia Antica until 2021. From the initial results it was possible to obtain graphic representations, numerical models, and orthophotos to be used as bases for multidisciplinary archaeological and historical studies, restoration and conservation interventions, and strategies for valorization and use by the Parco Archeologico dell'Appia Antica.
From the generated documentation, it was possible to understand the archaeological level, the morphometric characteristics of the mausoleum, the urban relationship between the mausoleum and the Appia Antica, and the topography of the area.

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NOTE

[1] Cf. Quilici 1989.

[2] Subjects responsible for the scientific collaboration agreement: for the Archaeological Park of Appia Antica, Director Simone Quilici; for the Department of Architecture at Roma Tre University, Professor Maria Grazia Cianci; for the Department of Humanities, Philosophical Studies, and History of Art at Tor Vergata University, Professor Lucrezia Spera. Officials of the Archeological Park: Architect Clara Spallino, Archaeologist Mara Pontisso.

[3] Technical data: UAV: DJI Matrice 210 V2. Camera: Zenmuse X5S. Sensor: CMOS 4/3", 17.30 x 13 mm. Resolution: 20.8 MP. Image pixels: 5280×3956 pixels. Flight height: below 25 meters. Number of shots: 820. Total acquisition time: 3 hours. Acquired area: approximately 100 x 80 meters.

[4] Cf. Barba et al. 2020. Micieli 2019.

[5] Cf. Remondino et al. 2011, pp. 25-31. Remondino & Rizzi 2010, pp. 85-100.

[6] The point survey with a total station and the corresponding georeferencing to the national reference system were not requested by the client, limiting the alignment to a simple orientation according to the north.

[7] Technical data: Laser scanner: Z+F IMAGER 5010X (MicroGeo). Number of stations: 48. Resolution: High. Total acquisition time: Approximately 15 hours. Acquired area: Approximately 100 x 80 meters.

[8] Cf. Cianci et al. 2020, pp. 605-618. Cianci et al. 2021, pp. 1-12. Colaceci et al. 2022, pp. 1-14.

[9] Cf. Bianchini 2014, pp. 763-768. El-Hakim et al. 2004, pp. 21-29.

[10] Cf. Bolognesi et al. 2014, pp. 113-19. Empler & Valenti 2020, pp. 80-87. Russo et al. 2019, pp. 549-568.

[11] Cf. Gaiani 2012, pp. 375-382. Guidi et al. 2009, pp. 39–55.

[12] Cf. Remondino 2011, pp. 1104-1138. Russo & Manferdini 2014, pp. 989-998. Cianci & Colaceci 2022, pp. 43-54. Cianci & Molinari 2021, pp. 133-140.

[13] Cf. Mateus et al. 2019, pp. 843-847.

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