Combining 3D Geometric Documentation with Infra-Red Thermography for Enhancing Cultural Heritage

Andrianna Kontoudaki[1], Sevasti Tapinaki[1], Ekaterini T. Delegou[2], Kyriakos C. Labropoulos[2], Antonia Moropoulou[2], Andreas Georgopoulos[1]

[1]Laboratory of Photogrammetry, School of Rural, Surveying and Geoinformatics Engineering, National Technical University of Athens, Greece

[2]Laboratory of Materials Science and Engineering, School of Chemical Engineering, National Technical University of Athens, Athens, Greece

kondoudaki@hotmail.gr, sevi@survey.ntua.gr,edelegou@central.ntua.gr,
klabrop@central.ntua.gr, amoropul@central.ntua.gr, drag@central.ntua.gr

Keywords: Cultural Heritage, Geometric Documentation, 3D Textured Model, NDT's, Infrared Thermography.

Abstract

The effective preservation and condition assessment of cultural heritage structures require advanced non-destructive testing (NDT) techniques that can identify structural issues without inflicting harm. This study proposes a novel methodology that integrates Infrared Thermography (IRT) with three-dimensional (3D) geometric documentation to create a comprehensive diagnostic system for heritage conservation. The method was applied to walls adjacent to the Library of Pantainos in the Ancient Agora of Athens, Greece. Geometric documentation was achieved through terrestrial surveying and photogrammetric techniques to generate detailed 3D models. For this purpose, non-destructive testing (NDT) techniques were applied. Specifically Infrared Thermography (IRT), high-resolution infrared thermograms were acquired using a thermal camera under controlled environmental conditions and systematically mapped onto the geometric documentation products, enabling precise localization of thermal anomalies and structural deterioration. In addition, digital microscopy (DM) was also employed to categorize stones and mortars.

This combined approach allows for precise localization and visualization of thermal anomalies, such as rising damp, material deterioration, and structural weaknesses. In Wall 1, the method identified rising damp accumulation leading to salt crystallization, while in Walls 2 and 3, severe material degradation and thermal stresses were observed. By integrating interdisciplinary data, this technique enhances the accuracy and efficiency of condition assessments, supporting informed conservation decisions. The study demonstrates the significant potential of combining IRT with 3D documentation to improve diagnostic capabilities and offers a robust framework for future applications in cultural heritage conservation.

1. Introduction

The protection of cultural heritage structures necessitates an interdisciplinary approach that integrates historical consciousness with advanced engineering methodologies to confront their multifaceted deterioration mechanisms. Monuments and historic structures are subject to damage risks arising from human activities, environmental stressors, and the inevitable effects of aging. As a result, it is critical to use diagnostic methods that can precisely determine their state without inflicting additional harm. Non-destructive testing (NDT) techniques have become more well-known in this regard as crucial means for the identification, tracking, and preservation of cultural assets (Moropoulou et al., 2020; Delegou & Moropoulou, 2022). These approaches provide essential information about structural health, material degradation, and subsurface anomalies, while preserving the integrity of the examined structures.

Among the suite of NDT methods, Infrared Thermography (IRT) stands out due to its ability to detect thermal anomalies that often correlate with hidden defects such as rising damp, corrosion, and material deterioration. High-resolution thermographic imaging, when combined with controlled environmental acquisition, enables early detection of such issues, supporting preventive conservation strategies (Antón & Amaro-Mellado, 2021; Adamopoulos et al., 2020). Furthermore, recent developments in 3D thermographic mapping have significantly enhanced the diagnostic value of IRT by allowing for the spatial localization of deterioration patterns directly on geometric models of heritage structures (Hellstein & Szwedo, 2016; Lagüela et al., 2012).

The evolution of 3D documentation technologies, particularly photogrammetric methods such as Structure-from-Motion (SfM) and Multi-View Stereo (MVS), has transformed the field of heritage documentation and conservation. These techniques facilitate the generation of highly detailed, accurate, and scalable 3D models that serve as baselines for condition assessment, monitoring, and restoration planning (Georgopoulos, 2016). The integration of thermal data onto these geometric models creates comprehensive 3D thermal maps, enhancing the diagnostic process by visualizing defects within their spatial context. Such combined datasets provide conservators and engineers with valuable information regarding the location, extent, and severity of deterioration phenomena.

In parallel, recent studies have explored the fusion of depth sensing technologies with thermal imaging to refine the 3D reconstruction of thermographic data. This fusion approach improves both the spatial accuracy and the interpretability of thermal anomalies, contributing to more reliable assessments (Cao et al., 2018). Additionally, the combination of NDT methods such as IRT and digital microscopy (DM) offers a multi-scale diagnostic framework, where IRT identifies macro-scale deterioration while DM provides microstructural characterization of building materials, including stone types and mortars (Moropoulou et al., 2020). This approach supports the accurate categorization of materials, the identification of decay mechanisms, and the selection of appropriate conservation methods.

This contribution has been peer-reviewed.
https://doi.org/10.5194/isprs-archives-XLVIII-M-9-2025-757-2025

Beyond diagnostics, the integration of 3D documentation and NDT data lays the groundwork for the development of digital twins—virtual replicas of physical assets which enable continuous monitoring, simulation, and maintenance optimization (Kim et al., 2022; Negri et al., 2021). Digital twins represent a paradigm shift in heritage conservation, promoting data-driven decision-making and proactive surveillance of structural condition.
This study is characterized by the required interdisciplinarity. Geometric documentation must be performed in such a way that it meets the needs of all involved; in fact, in most cases, it constitutes a prerequisite, as the adaptation of procedures and methods is often required due to the particularity of each project and object (Tapeinaki S. et al., 2021). This study builds upon these technological advancements by proposing a novel methodology which combines high-resolution infrared thermography, photogrammetric 3D documentation, and digital microscopy. By applying this integrated approach to selected walls in the Ancient Agora of Athens, Greece, the research aims to deliver a precise and holistic understanding of deterioration patterns, supporting informed conservation strategies. The proposed methodological framework aims to contribute to the continued evolution of heritage diagnostics by using cutting-edge NDT techniques and digital technologies for the sustainable preservation of cultural assets.

2. Methodology

2.1 Object of interest

In this study, a combination of infrared thermography and 3D geometric documentation was applied to three selected walls adjacent to the Library of Pantainos in the Ancient Agora of Athens, Greece (Figure 1). Built between 98 and 102 A.D., the Library stands near significant ancient structures, including these Walls (Figure 2).

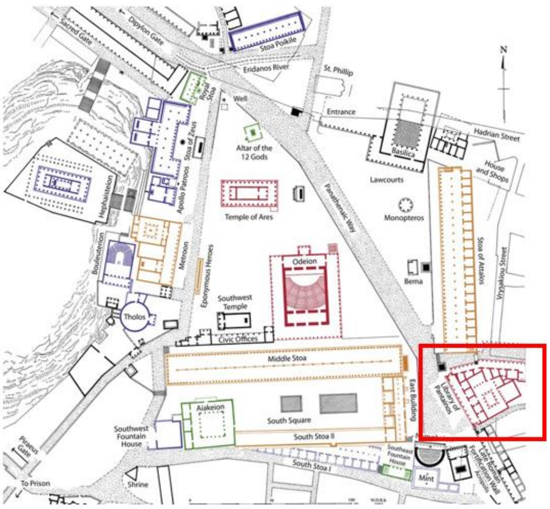


Figure 1. General plan of the Ancient Agora with the location of the Library of Pantainos indicated (red frame).

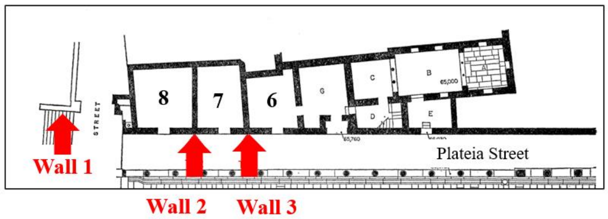


Figure 2. Plan of part of Plateia Street, the southern covered walkway and the underground rooms of the building.

Wall 1, located near the stairs linking the Ancient and Roman Agoras, is a well-preserved public structure built and constructed using a dry-stone technique. Beneath it, an ancient water pipe carries rainwater from the Acropolis. In contrast, Walls 2 and 3, situated between rooms 8 and 7 and between rooms 7 and 6 respectively, are rubble masonry walls, likely parts of residential or commercial buildings (Figure 3). These walls have undergone restoration interventions and exhibit varying materials and degrees of material decay, making them ideal cases for evaluating the effectiveness of the integration of Infrared Thermography (IRT) with three-dimensional (3D) geometric documentation.

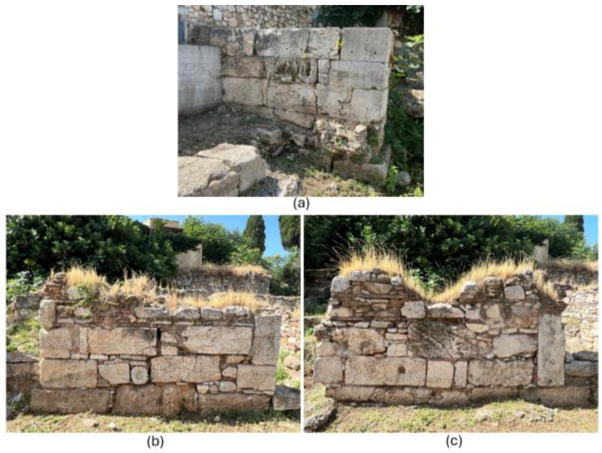


Figure 3. Representative photos of the structures adjacent to the Library of Pantainos: (a) Wall 1, (b) Wall 2, (c) Wall 3.

2.2 Data collection

The project's first step comprised the geometric documentation at a scale of 1:50. The essential quantitative and qualitative data were gathered by surveying the archaeological site using terrestrial measurements with a TopCon GPT-3003 total station and applying photogrammetric image acquisition with a Canon EOS 6D full-frame camera with a 24mm lens and a DJI Phantom 4 Pro UAV equipped with an FC7303 camera for specific wall facades of distinctive areas. The image processing phase was carried out using Structure-from-Motion (SfM) and Multi-View Stereo (MVS) algorithms, aiming to reconstruct the scene's geometry and camera movement and produce a dense point cloud and surface. These images were processed using Agisoft Metashape Professional software, resulting to a 3D texture model and an orthophoto.

The geometric documentation of the wider area was carried out for a parallel project (Tentoma 2024). A local reference coordinate system was established and used for referencing the coordinates of the essential ground control points. For the geodetic measurements the total station was used and the coordinates of the required points, such as targets for the point cloud registration and ground control points for the orientation of images were determined. This was important because georeferencing heterogeneous data to a common reference system enables their effective use in generating the requested products according to the required specifications. The positions of the survey stations were carefully selected considering the monument’s size and shape, accessibility, complete coverage of the object, mutual visibility between at least two other stations, and ground stability. The final triangulation adjustment produced horizontal and vertical coordinates, all within the predefined tolerances of ±0.005 m horizontally and ±0.015 m vertically.

The thermographic survey was conducted over three distinct sessions at different times of day and on separate dates in June 2024. Representative results from these inspections are presented below for the facades and structures of particular interest. Most temperature recordings and diagnostic interpretations derive from the Infrared Thermography (IRT) survey carried out on June 16, 2024. On the specified date, the facades under study were intentionally exposed to relatively uniform solar radiation during data acquisition, to ensure consistent and reliable thermal imaging conditions. Environmental conditions during the survey were recorded with an ambient air temperature of T = 32.5°C ± 1.5°C and relative humidity (RH) = 40% ± 4%, providing stable conditions for thermal imaging acquisition and analysis.

Thermal imaging was performed using a high-resolution FLIR T640 camera, capturing thermal and RGB images. Proper camera calibration, emissivity adjustments, and avoidance of extreme conditions ensured measurement reliability. Each IRT (Figure 4) image was also checked to ensure that at least three metal photogrammetric targets were visible, which are required for the creation of the three-dimensional model. The use of metal photogrammetric targets enables clear detection across thermal and visual datasets, as their low emissivity and high reflectivity enhance contrast in infrared images.

Figure 4. IRT image (a) and RGB image (b) and metal targets in red frames.

In this study, thermographic data was acquired during summer mornings, with the camera positioned approximately 4 meters from the target walls. Image acquisition followed the Structure-from-Motion (SfM) methodology, enabling texture projection onto the 3D model. Thermal images were taken orthogonally to the wall surface with 60-80% overlap and then with the camera tilted 30° upwards, downwards, and sideways. Subsequent data processing was carried out using Flir Tools software.

In addition to thermography data, Digital Microscope (DM) data was also collected (Figure 5). The results of DM enabled the observation of the texture, microstructure, and morphology of the building materials, allowing for the classification of different lithotypes and mortars.

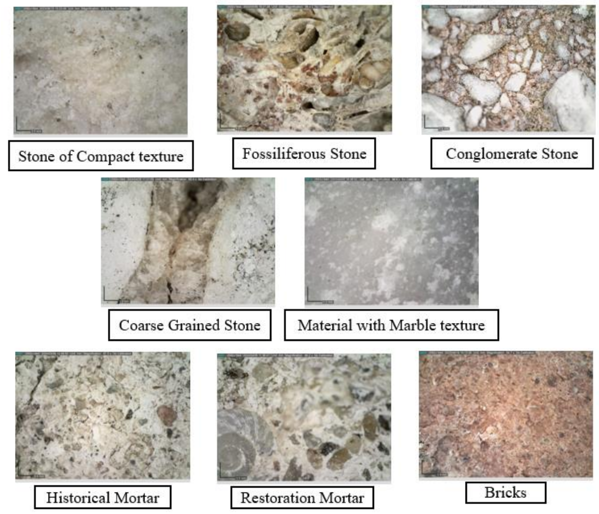


Figure 5. Digital microscopy images of the building materials.

2.3 Data processing

Firstly, all acquired images were oriented once again with high accuracy via the automated Structure from Motion (SfM) process. This aims, among others, to the creation of the correct shape of the object. In addition, it is crucial to confirm that every tie point is accurate. Control points with errors higher than 1 cm were eliminated, leaving 52 valid and well-distributed points. This was important to attain the desired final accuracy of 1.25 cm, as the precision of the ground control points (GCPs) had to be greater than the final intended accuracy. In Agisoft Metashape, optimization tools are used to refine camera alignment by minimizing reprojection errors and improving overall model accuracy. After the integration of GCPs, camera parameters such as focal length, principal point, and lens distortion coefficients are adjusted through the Optimize Cameras' function. This step is essential to correct geometric distortions, enhance the internal consistency of the model, and ensure accurate georeferencing. Following a successful orientation, the targets were found, and the coordinates were introduced to georeference the images and the sparse point cloud. Each cultural heritage building's orientated photos had a georeferencing precision of less than 1.2 cm. Next, the Multi-View Stereo (MVS) reconstruction methods were implemented to create the dense point clouds. A more consistent point cloud was created by further processing the point clouds to eliminate noise and mavericks.

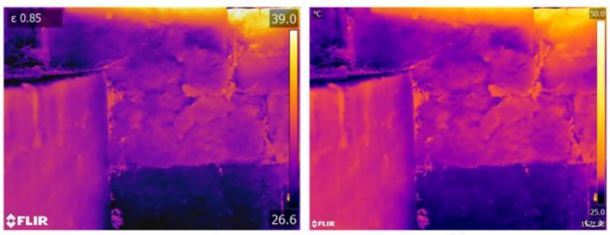
Since these models were utilized to produce all other required products, it was essential to create precise and integrated 3D models. The triangulated irregular network (TIN), which is a simple way of creating a surface from a collection of irregularly spaced points, was selected to represent the continuous surfaces. The points may be farther apart in regions with a smoother surface, but their density rises in regions with more severe relief. This decreases the number of triangles and points needed to model complex surfaces, which in turn lowers the file size. An accurate 3D representation (Figure 6) and an orthophoto (Figure 7) suitable for further analysis and documentation, were produced.

https://doi.org/10.5194/isprs-archives-XLVIII-M-9-2025-757-2025

Figure 6. 3D model of Walls in the Pantainos Library.

Figure 7. Orthophoto of the northern aspect of the southern wall of the staircase and rooms 6-7-8.

Each thermograph recorded maximum and minimum temperature values, with color palettes standardized such that the coolest temperatures appeared dark blue (almost black) and the warmest appeared light yellow (almost white). To generate a coherent 3D model with infrared texture mapping, thermographs were processed to unify the temperature range, ensuring consistent color representation. Following relevant testing, a temperature range of 25°C to 50°C was selected for all images (Figure 8).



(a) (b)

Figure 8. IRT image without processing (a), and with adjusted temperature range of 25°C to 50°C(b).

Finally, the careful application of the texture from the oriented RGB and IRT images, completed the detailed 3D textured models. Texture mapping onto the 3D model of the library section was performed using Agisoft Metashape Professional. The overall surface was segmented into distinct spatial units, with each unit receiving a texture map derived from the corresponding infrared thermograms. As a result, each wall was represented by a developed surface image containing the mapped thermal texture. For Wall 1 and for 2 and 3 combined, a resolution of 4096 × 4096 pixels was adopted, as this was found to be optimal for compatibility and performance across the various processing software (Figure 9).

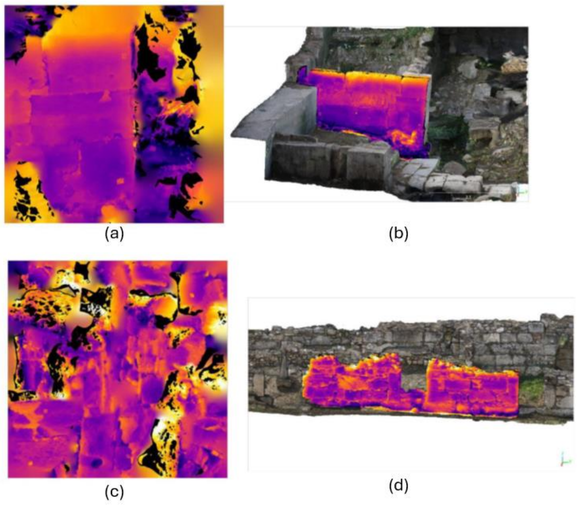
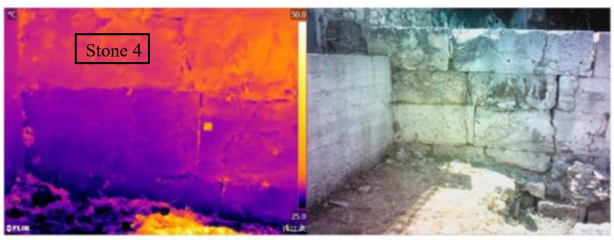


Figure 9. Texture map of Wall 1, as derived from thermograms (a), 3D model of Wall 1 with Thermal texture (b), Texture map of Walls 2 and 3, as derived from thermograms (c), 3D models of Walls 2 and 3 with Thermal texture (d).

3. Analysis and Evaluation

For the presentation and evaluation of IRT results, an IRT image and a RGB one with annotations are presented below for Walls 1, 2 and 3 separately. Figure 10 illustrates the lower left section of Wall 1, where its direct contact with the ground is observed. This area demonstrates increased thermal variability, with surface temperatures ranging from approximately 24°C to nearly 40°C. The lower portion of the wall is consistently depicted as cooler in the thermographic imagery, a clear indication of rising damp. Rising damp presence not only contributes to the reduced thermal reading but also exacerbates the deterioration processes affecting the masonry fabric.
Particularly noteworthy is the fossiliferous stone identified as "Stone 4" which exhibits an average surface temperature of approximately 29°C. Beyond thermal anomalies, this stone displays evident signs of material loss and structural compromise. Cracks and fissures are prominently visible, and the detachment of material fragments points to ongoing decay processes. Cumulative evidence suggests that rising damp penetration, combined with thermal stress and material deterioration, has significantly undermined the integrity of the stones in this section.



(a) (b)

Figure 10. IRT image revealing thermal anomalies (a), Corresponding RGB image of the same section of the Wall 1(b).

Figure 11 depicts the middle section of the wall, where a relatively small thermal variation is recorded between materials, with temperatures ranging from 28°C to 33°C. This moderate range is attributed to the predominance of stone masonry in this area, which ensures greater thermal uniformity. The geometric features of the stones, including characteristic tool marks such as putlock holes, are clearly discernible, alongside visible signs of material degradation.

Particularly significant is the stone 8 displaying the highest recorded temperature within this section. This stone is traversed by a wide, shallow crack that extends diagonally from the upper left corner to the midpoint of the opposite side, effectively bisecting the rectangular form of the block. The presence of this fissure highlights the material's progressive deterioration, likely exacerbated by thermal stress and weathering.

Furthermore, the fossiliferous stones identified as Stones 8, 10, 6, and 0 exhibit distinct thermal variations, which correspond to varying patterns of decay. In Stone 8, for example, thermal imaging reveals a notable 3°C increase in the area flanking the crack, where severe biodeterioration has been observed. In contrast, the right-hand section of the same stone, where a hardened crust has developed, shows comparatively lower temperatures. Meanwhile, the other fossiliferous stones demonstrate a higher degree of thermal homogeneity, closely matching the adjacent solid structural stones, suggesting less active deterioration in those blocks.

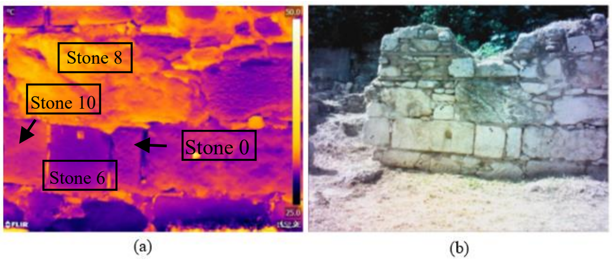


Figure 11. IRT image revealing thermal anomalies (a), Corresponding RGB image of the same section of the wall 2(b).

Figure 12 illustrates the central portion of the Wall that comes into direct contact with the ground. The geometric features of the stones are clearly discernible, including their outlines, their surface irregularities, and signs of material loss and cracking, which are indicative of ongoing weathering and structural deterioration.

Thermal imaging analysis reveals that the highest temperature readings are concentrated in the restoration mortar, suggesting its greater thermal absorption and retention capacity under the given environmental conditions. In contrast, the lowest temperature is recorded in the degraded conglomeratic stone identified as Stone 21. This cooler reading is attributed to the stone's direct contact with the ground, which exhibits elevated levels of rising damp. The presence of rising damp in the lower section significantly reduces surface temperature, further highlighting areas where rising damp is actively impacting the structure's material.

This pattern of temperature distribution not only underscores the differing physical responses of original and restoration materials but also provides valuable insights into the localized deterioration mechanisms, particularly in zones where masonry interfaces with ground.

Figure 12. IRT image revealing thermal anomalies (a), Corresponding RGB image of the same section of the Wall 3(b).

The three-dimensional model enhanced with infrared thermography texture offers a wide range of capabilities and applications for professionals engaged in the protection of Cultural Heritage. First and foremost, it spatially correlates the thermal distributions captured by thermographic imaging with the physical structure, effectively visualizing the temperature distribution of the object of interest within its spatial context.

Furthermore, it integrates the thermal variations observed in the masonry materials directly into the georeferenced three-dimensional surface model, enhancing the interpretive value of the data. This approach also facilitates improved classification of construction materials and deterioration patterns, as the infrared thermography data are accurately mapped to their precise locations within the structure. In addition, it offers a practical tool for measuring the affected areas, thus contributing to the condition assessment.

Finally, the model provides an advanced tool for the monitoring, evaluation, and assessment of the preservation state of masonry structures, supporting more informed conservation and restoration interventions.

Specifically, for Wall 1 (Figure 13), the analysis unequivocally confirms the accumulation of rising damp in the lower masonry sections, a condition that promotes the transport, crystallization, and recrystallization of salts with potentially harmful consequences for the materials. Moreover, the thermographic survey identifies significant degradation affecting the central intermediate stone, signaling advanced material weakening. Notably, bricks located in the lower right of the wall exhibit elevated thermal responses in comparison to adjacent stone elements, suggesting variations in material composition or rising damp, which may account for differential thermal behavior and accelerated decay processes.

Figure 13. Texture IRT of Wall 1.

In the case of Walls 2 and 3 (Figure 14), the findings indicate that several structural materials, particularly stone elements, exhibit pronounced signs of erosion and advanced weathering. Furthermore, mortars in these sections are observed to accumulate higher temperatures, creating sharp thermal gradients between adjacent materials. These thermal differentials generate internal stresses that compromise intermaterial cohesion, leading to progressive joint loosening and cracks, with detrimental effects on the structural stability of the masonry system. Additionally, evidence of rising damp is consistently recorded along the essential sections of the walls, especially in areas constructed with conglomerate stones, further highlighting the susceptibility of these elements to rising damp deterioration.

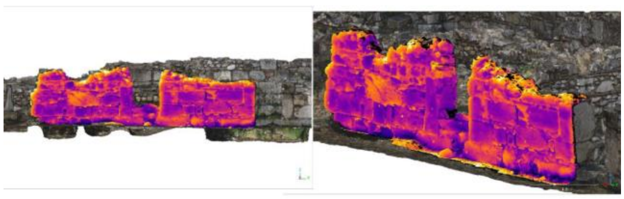


Figure 14. Texture IRT of Walls 2 and 3.

As a continuation of the present research, the results were further developed in a subsequent study focusing on the detailed digitization of building materials and decay patterns on orthophotos. This allowed for the spatial representation of these data and their integration into a GIS environment using the open-source QGIS platform. The GIS was designed to record, manage, analyze, and visualize both qualitative and quantitative information derived from the interdisciplinary investigation of the monument. Thematic maps of building materials and decay patterns were created, providing valuable information about environmental impact assessment (Figure 15).

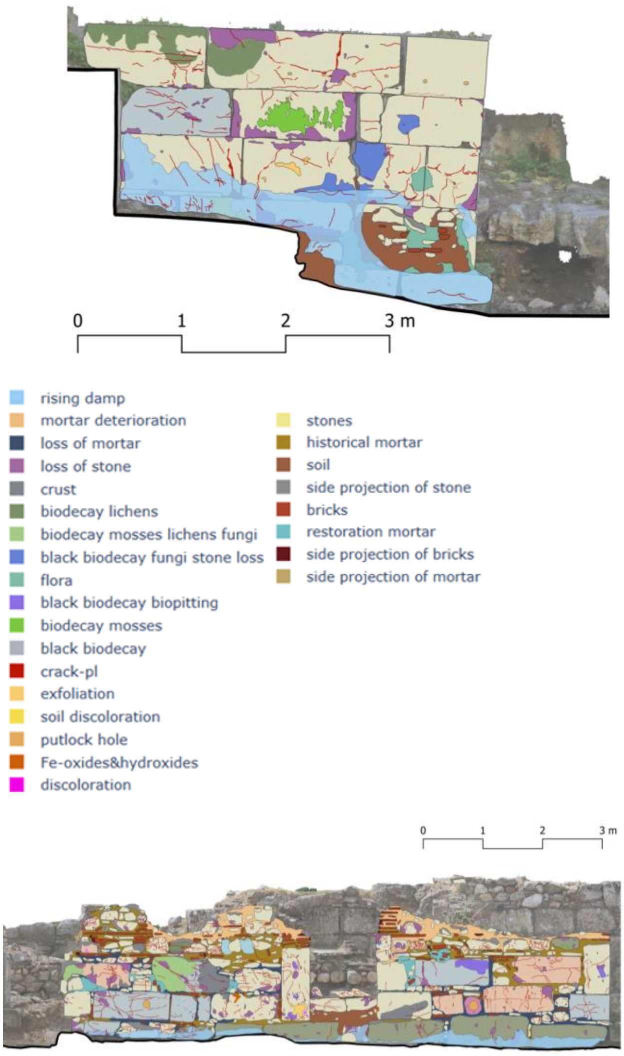


Figure 15. Building material and Decay thematic map and legend of Wall 1(up) and Walls 2 and 3 (down).

4. Concluding Remarks

This study proposes a comprehensive and innovative methodological framework for the integration of Infrared Thermography (IRT) with high-resolution three-dimensional geometric documentation in the assessment of cultural heritage structures. The combined application of thermal imaging and photogrammetric modelling demonstrably enhances both the visualization and analytical capabilities available for evaluating the structural and thermal behavior of historic buildings. This integrated approach yields critical insights into patterns of material deterioration, paths that rising damp entry, and stresses of temperature variations, all of which are fundamental considerations in the formulation of effective conservation strategies.

Overall, this research represents a significant advancement in the fields of photogrammetry and heritage conservation, offering a novel paradigm for the fusion of thermographic and geometric datasets in diagnostic practice. By refining and expanding the methodology, future work has the potential to further increase the applicability and impact of this approach within the domain of cultural heritage preservation.

Acknowledgements

The authors would like to acknowledge the contribution of the Ephorate of Antiquities of Athens for granting us access to the monument, which was essential for the collection of data and measurements. Their support and cooperation were invaluable for the completion of this study.

References

Moropoulou, A., Bakolas, A., Delegou, E. T., & Karoglou, M. (2020). Innovative methodologies combining NDT and microstructural analysis in heritage materials assessment. *Construction and Building Materials*, 245, 118422.

Delegou, E. T., & Moropoulou, A. (2022). Advances in Non-Destructive Testing and Evaluation for Masonry Diagnostics. In *Advances in Heritage Science and Technologies* (pp. 127-148). Springer.

Antón, D., & Amaro-Mellado, J. L. (2021). Engineering graphics for thermal assessment: 3D thermal data visualisation based on infrared thermography, GIS and 3D point cloud processing software. *Symmetry*, 13(2), 335.

Adamopoulos, E., Volinia, M., Girotto, M., & Rinaudo, F. (2020). Three-dimensional thermal mapping from IRT images for rapid architectural heritage NDT. *Buildings*, 10(10), 187.

Hellstein, P., & Szwedo, M. (2016). 3D thermography in non-destructive testing of composite structures. *Measurement Science and Technology*, 27(12), 124006.

Lagüela, S., Armesto, J., Arias, P., & Herráez, J. (2012). Automation of thermographic 3D modelling through image fusion and image matching techniques. *Automation in Construction*, 27, 24-31.

Georgopoulos, A. (2016). 3D GEO: An alternative approach. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *4*, 99-106.

Cao, Y., Xu, B., Ye, Z., Yang, J., Cao, Y., Tisse, C. L., & Li, X. (2018). Depth and thermal sensor fusion to enhance 3D thermographic reconstruction. *Optics Express*, 26(7), 8179-8193.

Kim, J., Lee, S., & Park, J. (2022). Digital twin-based structural health monitoring integrating 3D thermal imaging data. *Sensors*, 22(9), 3345.

Kontoudaki, A., 2025. Holistic 3D documentation of geometry, materials and decays. The case of the structures adjacent to the Library of Pantainos in the Ancient Agora of Athens. MSc thesis, NTUA. Master of Protection of Monuments (Athens) (degree granting institution) Athens: NTUA, School of Chemical Engineering, 2025 (https://dspace.lib.ntua.gr/xmlui/handle/123456789/60554 (in Greek))

Kontoudaki, A., Delegou, T. E., Tapinaki, S., Lampropoulos,C. K., Georgopoulos, A. & Moropoulou, A. (2025). Mapping and analysis of Building Materials and Decay Pattersn using GIS: The case of Structures Adjacent to the Pantainos Library in the Ancient Agora.In *Advances in Nondestructive Evaluation Technologies for the Preservation of Cultural Heritage: Selected works from the TMM-CH 2025 (in press), Springer International Publishing.*

Negri, E., Fumagalli, L., & Macchi, M. (2021). Digital twin integration with non-destructive testing for maintenance optimization. *Computers in Industry*, 131, 103516.

Tapinaki, S., Skamantzari, M., Anastasiou, A., Koutros, S., Syrokou, E., & Georgopoulos, A. (2021). 3D holistic documentation of heritage monuments in Rhodes. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *46*, 739-744.

Tentoma, N., 2024. Virtually Reconstructing the Past. Identifying Authenticity in a Virtual Reality Application for the Library of Pantainos in Athens. MSc thesis, KU Leuven. Faculteit Ingenieurswetenschappen. Opleiding Master of Conservation of Monuments and Sites (Leuven) (degree granting institution) Leuven: KU Leuven. Faculteit Ingenieurswetenschappen, 2024 (https://kuleuven.limo.libis.be/discovery/fulldisplay?docid=alma9995039881401488&context=L&vid=32KUL_KUL:KULeuven&search_scope=All_Content&tab=all_content_tab&lang=en)