3D Thermal-Photogrammetric Modeling with an Integrated Digital Platform for Heritage Preservation

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Abstract

Nowadays, digital technologies are a fundamental component of cultural heritage conservation, providing accurate data for informed intervention. The growing complexity of conservation requires the integration of data from multiple sources to fully understand the condition of an asset. This research explores the combination of photogrammetry and thermography as a high-performance non-destructive diagnostic tool. The integration of these data sets enables accurate spatial mapping of thermal defects within a 3D environment, providing a more in-depth view of structural health than standalone methods. This combined process is particularly applicable to assessing material conditions, inspecting subsurface defects, and gaining a better understanding of structures.
This study proposes a workflow designed to accelerate and simplify the integration of these techniques. The main objective is to generate a single informative point cloud that can be published on an interactive online platform for greater accessibility and analysis. The methodology was applied to a case study within the Royal Palace of Caserta, a UNESCO World Heritage Site. Specifically, the research focused on the bathroom of the Royal Apartments to investigate significant cracks identified on the decorated walls. Thanks to advances in automation in 3D thermographic modelling, this research provides a more efficient framework for interpreting the condition of cultural heritage and supporting long-term conservation strategies.

1. Introduction

In recent years, the use of digital technologies has become increasingly widespread in the scientific field, where traditional techniques have been almost completely overtaken. In the field of cultural heritage, one of the main issues remains the conservation of buildings and artefacts, so the need to know the current state of the assets is of primary importance. Therefore, digital surveying techniques are almost always the starting point of the intervention workflow, providing the precise geometries and details of the object to be worked on (Elefante et al., 2025). At the same time, the need to have more information available simultaneously makes the issue of data integration increasingly important.
The growing combination of thermography and photogrammetry is one example. This offers high-performance, non-destructive diagnostic analysis technology, useful in architecture for interpreting the condition of cultural heritage and promoting its preservation (Sutherland et al., 2023). Both techniques provide raw data that can be used for a wide range of operations. Photogrammetry produces accurate, formal 3D models, capturing complex geometry and visual attributes. Thermography, on the other hand, captures surface temperature distribution, identifying not-so-obvious conditions such as penetration of moisture and degradation of materials. The integration of the two techniques offers the potential to identify thermal anomalies in a properly spatial 3D model with significantly more information than the standalone technique. This combined process is particularly applicable to assessing material conditions, inspecting subsurface defects, and gaining a better understanding of structures. Advances in automation are continuously improving combined procedures for 3D thermographic modelling, offering greater precision and wider applicability to architectural works. It is in this context that the present research is situated, testing a workflow to accelerate and simplify data integration to obtain a single informative point cloud, which is then published on an interactive online platform. The process was applied on the Royal Palace of Caserta, a UNESCO World Heritage site, as part of the 2022 PNRR Call for Proposals SINERGY project, specifically in the bathroom of the Royal Apartments, due to the presence of large cracks identified on its decorated walls (Fig. 1).

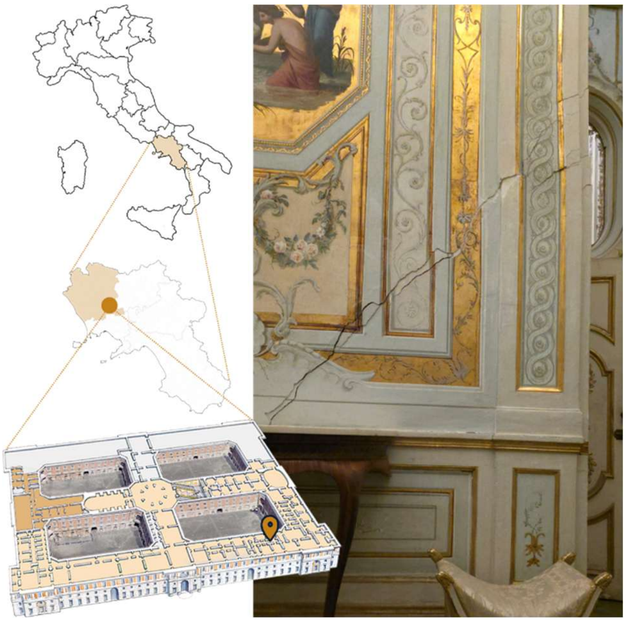

Figure 1. On the left: the Royal Palace of Caserta framed in Campania region and Italy; on the right: one of the cracks on the decorated wall of the bathroom of the Royal Apartments.

1.1 Methodological notes

Conservation research has progressively moved towards more quantitative and objective methodologies, integrating non-destructive investigation techniques (NDT) and advanced monitoring systems. Amongst NDT, infrared thermography (IRT) has proven useful for identifying surface and sub-surface anomalies (Guolo et al., 2023; Pitarma et al., 2019), although the interpretation of thermograms on complex historical objects (Rippa & Mormile, 2021), such as those with gilding or paintings, can be complicated by variations in emissivity and reflections, often necessitating data correction procedures. Integrating these data with accurate 3D models (Morena et al., 2021) also provides a spatial platform for visualising and analysing the information in a correlated manner.
A lot of researchers have confronted this theme with different approaches. In some cases, this goal was achieved directly from the traditional photogrammetric workflow, using thermal images as sources for the construction of the point cloud, matching colours with the temperature scale obtained from the camera (Patrucco et al, 2020). In other cases, the thermal images were preliminary modified to be ready to be integrated into the photogrammetric workflow (Griffo et al., 2019; Lagüela et al., 2012; Qiu et al., 2025; Sutherland et al., 2025). A plurality of studies focuses instead on the integration of thermal data into point clouds using rigorous mathematical approaches (Adamopoulos et al, 2021; Chromy & Klima, 2017; Hadabay et al., 2019; Ramm et al., 2024), making it difficult and time consuming to replicate the methodology.
This study aims to test a different approach simplifying the process and making it faster. The experimented workflow (Fig. 2) is carried out entirely within Agisoft Metashape, obtaining in a first phase a point cloud in a traditional way, and then projecting thermal images on it. Simultaneously, an online interactive platform is structured, where the obtained data is integrated and can be consulted through a user-friendly interface to visit the model and report damages.

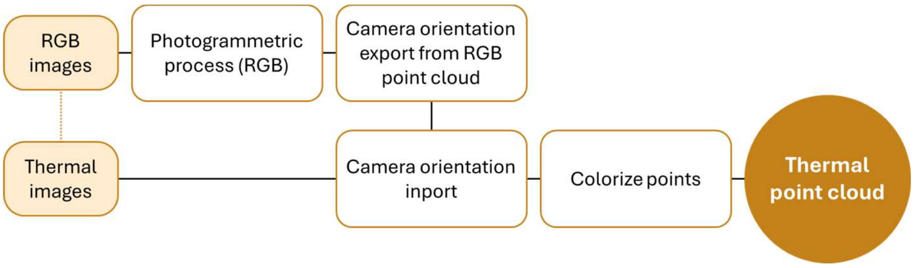

Figure 2. Workflow tested in the study to obtain a thermal point cloud.

2. Materials and methods

2.1 Case study and multi-sensor data acquisition

The experimental site is the Royal Bathroom within the Royal Palace of Caserta, a confined space characterized by complex decorative elements, including gilded ornaments and intricate plasterwork. The primary object of study is portion of wall with a significant structural crack, probably caused by the bombs during World War II. The room's small dimensions posed a severe constraint on the acquisition distance, being maximum 2.50m (Fig. 3), resulting in a limited Field of View (FOV) and a high risk of perspective distortion. These environmental conditions necessitated a multi-sensor approach capable of operating at close range while maintaining high geometric accuracy.
Data acquisition was performed using a dual-sensor strategy to capture both visible and thermal infrared (TIR) spectra. Visible-light imagery was captured using a Samsung Galaxy S25 Ultra, with its high-resolution 23mm wide-angle lens, set to ISO 1600 and shutter 1/60s, to record fine-grained textures and gilded details. Thermal data were collected using a FLIR A700 model infrared camera with a microbolometric sensor and a 24° lens.
The images were captured in a standardized orbit shooting sequence so that there would be a considerable amount of overlap (approximately 80-90%) between two consecutive images for reconstruction purposes. To ensure geometric consistency, the two devices were mounted with their camera lenses aligned along the same optical axis. The smartphone was chosen specifically to ensure that the acquisition distance remained virtually identical for both sensors, minimizing parallax errors. A total of 52 frames for each set of images were captured following a convergent parallel-axis trajectory (Fig.4).
As a preliminary step to data integration, the thermal images were pre-processed using FLIR Research Studio software. First, the thermal scale of all frames was standardised to ensure radiometric consistency across the entire dataset. Next, a Gaussian filter with a 3×3 kernel and standard deviation (σ) of 3 was applied to attenuate high-frequency noise and improve the overall quality of the thermal data.

2.2 Photogrammetric process with camera orientation applied to thermal sensors

The photogrammetric workflow was executed in Agisoft Metashape Professional. Due to the high resolution and superior feature detection of the RGB dataset, it was used to generate the primary 3D geometry via Structure from Motion (SfM) and Multi-View Stereo (MVS) algorithms. In contrast, the thermal images proved insufficient for independent point cloud generation; the low pixel density combined with the close acquisition distance prevented the software from identifying enough stable tie points.
To integrate the thermal data, the exterior orientation parameters (EOPs) were transferred from the RGB model to the thermal dataset. For this operation, it was necessary that the image sources had the same names, so a preliminary operation was to rename the two sets of frames as needed. Ten different export/import formats for camera orientation were evaluated to identify the highest spatial accuracy. Among these (summarized in Table 1), the PATB Camera Orientation (Fig. 5-a) format was selected as the optimal solution, as it provided the most stable coordinate transformation between the visible and infrared image blocks.

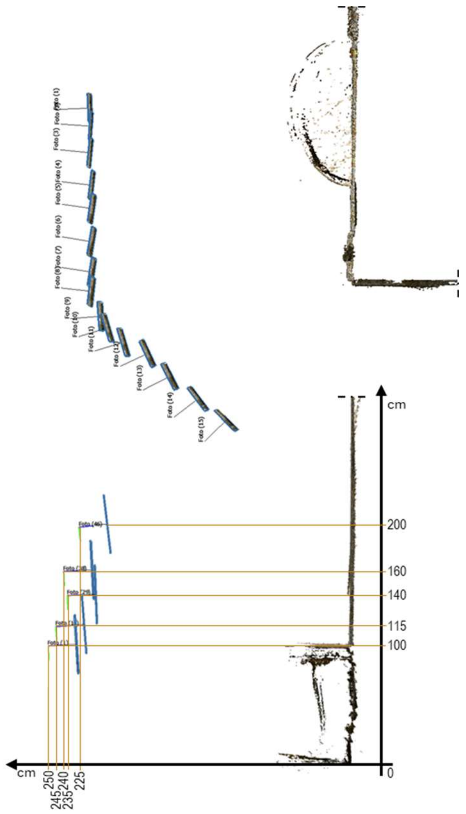

Figure 3. Horizontal (top) and vertical (bottom) shooting sequence during data acquisition.

Figure 4. The two devices with their camera lenses aligned along the same optical axis and the two sets of frames.

PATB (Perspective/Aerial Triangulation Block) camera orientation defines a standard coordinate system where the camera's optical centre is at the scene's origin, the view points along the -Z axis, the image's Y-axis points up, and the X-axis points right, crucial for photogrammetry to align aerial images and build 3D models, often requiring rotation adjustments (kappa) from map north for accurate geo-referencing.
Since the FLIR A700 was not automatically recognized by the photogrammetry software's internal database, a manual Interior Orientation (IOP) calibration was conducted. This involved defining the focal length (fixed at 17 mm) and calculating the physical pixel size obtaining approximatively 11µm (Fig. 5-b).
Once calibrated, the thermal frames were projected onto the high-density RGB point cloud (Fig. 6). However, discrepancies in the Field of View (FOV) meant that thermal frames covered significantly smaller wall sections than the RGB counterparts. The resolution of the frames also is different, being the RGB 8160x3768px (≈31MP), while thermal ones are 640x480px (≈0.3MP) (Fig. 7-a). Furthermore, thermal "noise" was observed: identical architectural elements showed varying temperature readings across different frames. The colour variation observed in different frames is attributable to variations in the surrounding environment (presence of people, heat sources or environmental conditions), which alter the infrared radiation reflected from the surface and therefore the apparent temperature as measured by the thermal imaging camera. (Fig. 7-b).

Exporting Settings	Import
Agisoft XML (*.xml)	No alignment
PATB Camera Orientation (*.ori)	Correct alignment
BINGO (*.dat)	No alignment
Inphoto Project File (*.prj)	Invalid coordinate system
Blocks Exchange (*.xml)	No alignment
Bundler (*.out)	Correct alignment, wrong position
Realviz RZML (*.rzml)	No alignment
N-View Match (*.nvm)	Single image aligned
Alembic (*.abc)	No alignment
Autodesk FBX (*.fbx)	No alignment

Table 1. Export/import formats for camera orientation that were evaluated for the workflow.

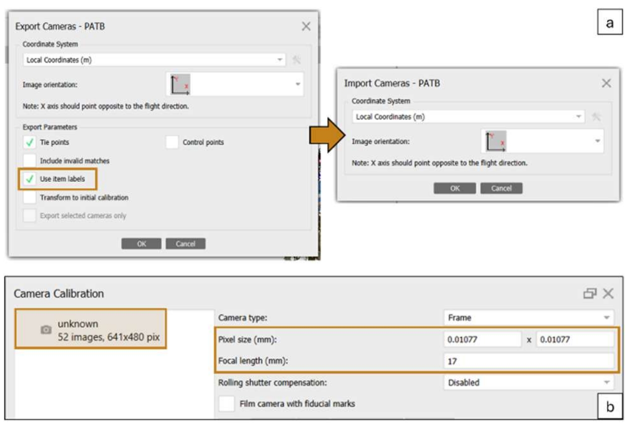

Figure 5. a) Export/import settings using PATB format; b) Camera calibration for the thermal sensor that was not automatically recognized.

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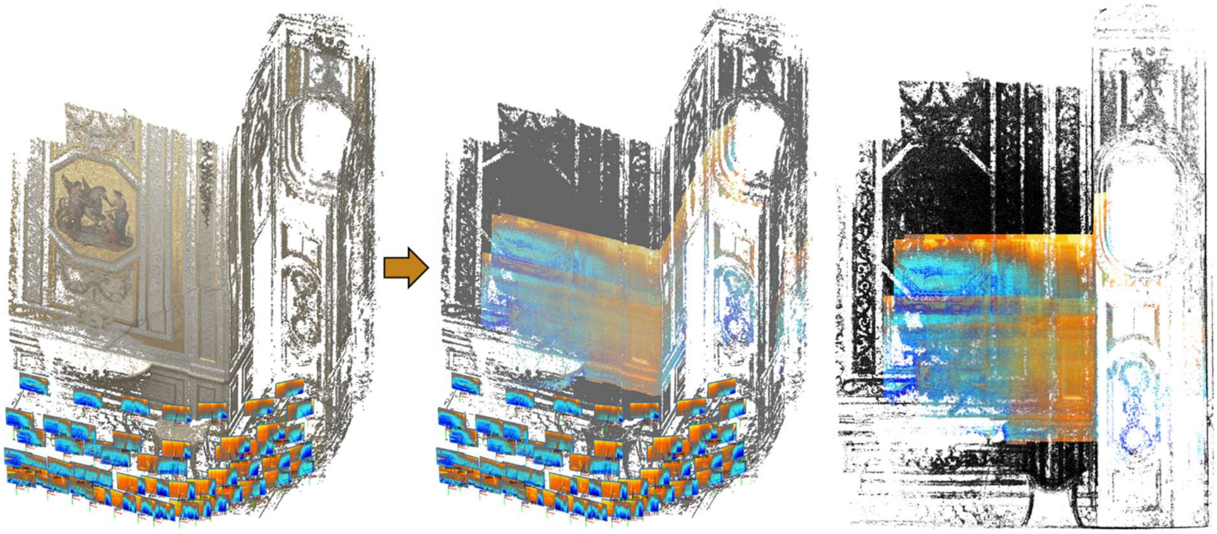

Figure 6. Projection of thermal images on the RGB point cloud

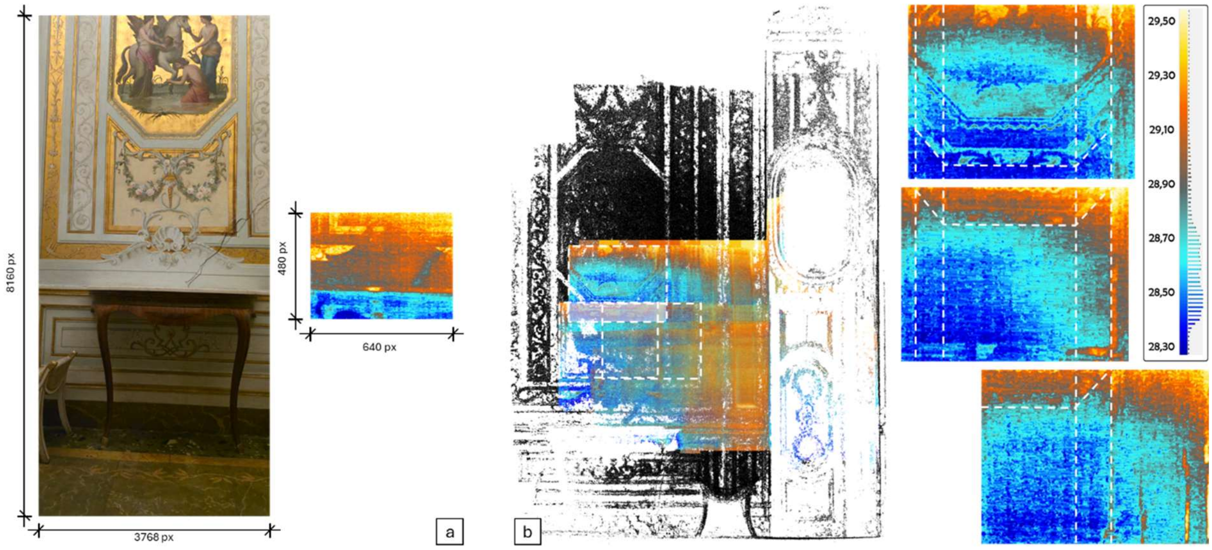

Figure 7. a) Difference between sizes of the two sets of images, RGB and thermal frames; b) colour variation on the same architectural element observed in different frames, due to alteration in infrared radiation because of variations in the surrounding environment.

2.3 Dissemination in a web-based interactive platform

The final stage of the methodology focused on the implementation of a web-based interactive platform (Fig. 8), bridging the gap between raw multi-modal data and actionable conservation insights.

The processed 3D thermal model was integrated into a bespoke online digital platform, designed as both a centralized storage facility and a high-performance visualization tool. The technical architecture of the platform was built using WebGL and the Three.js library, enabling the fluid rendering of high-density point clouds directly within a web browser (Abergel et al., 2023; Arese et al., 2025). This user-friendly interface allows stakeholders to interactively navigate the model, toggling between high-resolution RGB textures and thermal false-colour mappings.

The diagnostic phase involves a rigorous interpretation of the thermal data to detect anomalies. By analysing thermal hotspots, gradients, and specific patterns, a user can identify architectural defects that are often invisible to the naked eye, such as thermal bridges, localized moisture ingress, or internal heat gain within the masonry. Each identified anomaly can be logged within the platform as a spatialized "Warning". These alerts are pinned to precise 3D spatial coordinates (X, Y, Z) on the model and enriched with a comprehensive metadata schema (Hak et al., 2008), including:

- Severity Levels: Categorized as mild, moderate, or severe to prioritize conservation efforts.
- Descriptive Documentation: Detailed narratives of the observed thermal behaviour.
- Intervention Strategies: Recommended technical actions based on established conservation protocols.

The platform's backend facilitates the generation of customized, detailed reports, this allows for the longitudinal monitoring of the Royal Palace's structural health, ensuring that data is accessible for multi-disciplinary teams. Ultimately, this integrated use of thermography and photogrammetry provides a powerful non-contact diagnostic tool, significantly improving the decision-making process in architectural engineering and cultural heritage conservation.

3. Results and conclusions

3.1 Discussion

The experimental workflow successfully produced a multi-modal 3D representation of the Royal Bathroom's wall, effectively bridging the gap between high-resolution geometric documentation and thermal diagnostic analysis.
The primary result was the generation of a unique informative point cloud where each vertex contains both RGB values and thermal data. The transfer of Exterior Orientation Parameters (EOPs) via the PATB format proved to be the most robust method, maintaining a coherent alignment between the visible-light and infrared datasets, thus bypassing the limitations of the thermal sensor's low resolution.
From a diagnostic perspective, the integrated model provided a clear visualization of the structural crack and the surrounding gilded ornaments.
The thermal mapping made it possible to report thermal discontinuities or identify variations in material density or localized air infiltration. However, some issues emerged, such as the "thermal noise" caused by environmental factors, which not always allows to recognize a unique value for temperature in a point.

The web-based interactive platform successfully hosted the processed data, demonstrating high performance in rendering and interact with the point cloud. Testing confirmed that the interface allowed for the seamless "pinning" of spatialized warnings. The ability to toggle between the visible state and the thermal state in a 3D environment provided a superior cognitive understanding of the pathologies compared to traditional 2D thermogram analysis.

3.2 Future developments

Building upon the successful implementation of this simplified workflow, several avenues for future research have been identified to enhance the precision, automation, and diagnostic depth of the methodology.
A primary technical objective involves the mitigation of environmental "thermal noise." To address the thermal drift, future tests could focus on the implementation of automated frame-averaging algorithms and controlled acquisition protocols to stabilize temperature readings across the dataset.
On the analytical front, the research aims to integrate Machine Learning (ML) algorithms directly into the web-based platform. By training neural networks to recognize specific thermal signatures associated with moisture or delamination, the system could transition from a manual reporting tool to an automated diagnostic assistant. Additionally, the plan is to upgrade the platform to a multi-temporal (4D) monitoring system. By uploading and comparing datasets captured at different seasonal intervals, restorers will be able to track the thermal behaviour of objects.

Figure 8. Preview of the interactive online platform with the insertion of a warning at a point identifying an anomaly.

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