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Integrating geomatic high-detail surveying and thermography for the documentation of historical masonry

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Abstract – The integration of infrared thermography (IRT) with high-resolution 3D surveying represents an effective approach in support of non-destructive diagnostics applied to heritage materials. While there has been increasing interest in this area, the numerical incorporation of thermographic data into spatially accurate 3D models poses significant challenges, particularly when it comes to embedding quantitative temperature data directly into geometric datasets. This study introduces a structured and replicable workflow designed to facilitate this numerical integration through the generation of a thermal point cloud, wherein each 3D point is associated with corresponding temperature values. The proposed methodology was applied to a historic masonry wall at the University of Bologna, which exhibited both structural and biological deterioration, thus providing an ideal case study to test the robustness of the approach.

Data acquisition was carried out using high-resolution photogrammetry, achieving a sub-millimetric Ground Sampling Distance (GSD), alongside terrestrial laser scanning (TLS) and calibrated thermographic imaging to ensure both geometric accuracy and thermal reliability. A semi-manual tie-point-based alignment approach was employed to estimate camera pose for both RGB and thermal imagery simultaneously, with scaling supported by data obtained from the laser scanning process to achieve the final integrated dataset. The resultant thermal point cloud enhances analytical potential, enabling spatially contextualized thermal diagnostics and allowing deterioration patterns to be examined in relation to accurately reconstructed geometric features. Overall, this research addresses current limitations within the field and demonstrates a scalable and adaptable framework for the integration of thermal and spatial data in the realm of architectural diagnostics, opening possibility for more advanced, data-driven conservation and monitoring practices.

I. INTRODUCTION

Infrared thermography (IRT) and three-dimensional (3D) surveying are consolidated technologies in the fields of heritage building inspection, documentation, conservation and monitoring. Both these methodologies bring their own set of strengths: IRT allows inspection of thermal variations that can be indicative of underlying material characteristics, thermal behaviors, and degradation phenomena (Sutherland et al., 2023), while 3D surveying techniques, such as photogrammetry and laser scanning, deliver spatially accurate reconstructions of surface morphology (Guarnieri et al., 2006). When these techniques are integrated, they provide multi-layered data inspection that can significantly enhance and assist processes related to conservation and restoration efforts (Lagüela López, 2014; Scaioni et al., 2017; Trevisiol et al., 2021; Bitelli et al., 2020).

In the last years, a growing body of research has sought to explore the potential benefits of combining IRT with 3D surveying methods. For instance, Alba et al. (2011) introduced a novel thermographic-3D fusion method based on stereo-matching techniques, demonstrating improved diagnostics for building facades. Similarly, Patrucco et al. (2022) illustrated how photogrammetric models could be enhanced with thermal textures; however, they also highlighted the limitations associated with low-resolution thermal imagery when utilized as geometric contributors.

Costanzo et al.(2014) took a significant step forward by proposing the generation of thermal point clouds for defect detection, although their approach primarily yielded visual outputs lacking comprehensive numerical integration. Griffo et al. (2019) underscored the importance of spatial control in aligning thermal imagery with datasets acquired through laser scanning technologies. Yet, limitations are observed in incorporating temperature data numerically within these frameworks.

A persistent limitation observed across these various approaches is the tendency to treat thermographic data as visual overlays. Temperatures are often represented as color gradients mapped onto surface textures or 3D meshes, resulting in a lack of direct encoding of thermal information within the underlying data structure (Previtali et al., 2013), (Patrucco et al., 2020). Consequently, analytical operations—such as filtering based on thermal ranges or cross-referencing temperature data with material properties—become challenging or unfeasible within conventional 3D point cloud platforms.

In response to these challenges, this project aims to advance the integration of thermal and spatial datasets by creating a numerical thermal point cloud, where each 3D point is associated with a temperature value. This approach allows for querying, filtering, visualization, and comparative analysis of thermal data in a spatially aware manner. The proposed methodology employs a hybrid workflow that synergizes photogrammetry and IRT, with alignment and scaling facilitated through terrestrial laser scanning (TLS). The test area was a historic structure at the University of Bologna, which exhibited signs of physical and biological deterioration, as described in the following section.

II. METHODOLOGY

2.1 Case Study

The chosen case study focused on a section of the exterior wall of the Clinic for Nervous and Mental Diseases located within the University of Bologna campus (Fig. 1).

The construction of the building began in 1930 under the direction of Prof. Carlo Ceni, based on the project made by Engineer E. Boselli. The clinic aimed to become the most advanced neuro-psychiatric facility of that time. It responded to the growing need for specialized mental health treatment and psychiatric research (Bandini, 2019). The complex includes multiple two-story buildings; the central one hosted health offices, lecture halls, and therapy rooms. Separate wings were designed for male and female patients, each with dedicated neurological and psychiatric areas, and courtyards. Additional structures include a neurosurgery pavilion, scientific laboratories, and a library.

Until 2014, the building operated as a mental health clinic. Since then, it has housed the University of Bologna's Faculty of Architecture and Engineering.

The façade of the building reflects a synthesis of post-Frech Revolution stylistic influences, marked by a shift toward rationalism, functional clarity, and elegance. The design balances structural rigor with decorative refinement, exemplified by a neoclassical portal featuring two semi-columns that denote the building's institutional significance. Large architrave windows on the upper floor enhance verticality and interior illumination, aligning with early 20th-century ideals of hygiene and transparency in medical architecture. The first floor is characterized by the presence of double windows, framed by articulated moldings and tympanums, introducing rhythm and refinement to the composition. A prominent projecting cornice adorned with metopes and triglyphs, along with a stone plaque bearing the clinic's name, reinforces the building's civic and cultural role. This careful interlay of functional and symbolic elements positions the façade as a representative example of Italian institutional architecture from the early 20th century.

The wall in analysis exemplified classic deterioration patterns commonly associated with aging and environmental exposure, including the accumulation of black crust, the proliferation of moss, and the presence of micro-cracks. These features, depicted in Fig. 2, provided a pragmatic context for evaluating the integration of thermal and spatial data within a real-world setting. Although the architectural significance of the wall may not be particularly notable, its condition and the types of deterioration present created an ideal scenario for testing our workflow under realistic lighting conditions, environmental influences, and accessibility constraints.

Figure 1. The Palace Façade

Figure 2. A detail of the portion of the wall under inspection, showing signs of degradation

2.2 Data Acquisition

The photographic data acquisition was conducted using a Canon EOS 6D camera, equipped with a full-frame CMOS sensor (20.2 MP) and a 24–70 mm lens. A total of over 90 images were taken in RAW format, captured under diffuse daylight to minimize shadow contrasts that could affect the photogrammetry outcomes. The camera settings were optimized for achieving a suitable depth of field (ranging from f/11 to f/16) and reducing ISO noise (set between ISO 100 and 200). Close-range photographic coverage was essential to achieve a ground sample distance (GSD) of approximately 0.5 mm/pixel.

Thermal data were collected using a FLIR P-620 infrared camera (Fig. 3), which features a resolution of 640 × 480 pixels, a sensitivity of less than 0.06°C, and an accuracy of ±2°C. A total of twenty thermal images were captured under consistent environmental conditions, specifically around 10 a.m. with an ambient temperature of 18°C and relative humidity at 60%. To ensure the accuracy of the thermal data, a matte black calibration plate with an emissivity of approximately 0.97 was used for on-site emissivity calibration.

Figure 3. *Thermal data acquisition*

The resulting thermal images were exported as 32-bit grayscale TIFF files using FLIR Tools, preserving the absolute temperature values for each pixel (Fig. 4). This coordinated capture of visible and thermal imagery laid the foundation for the integrative methodologies applied in subsequent analyses, ultimately enabling the creation of a comprehensive thermal point cloud for the subject wall.

A TLS survey was conducted with a Leica RTC360 laser scanner, offering a declared point precision of 1.9 mm at 10 m. The scan data served as a geometric reference for aligning and scaling the image datasets through control points in the photogrammetric pipeline.

Figure 4. An example of raw thermogram (uncalibrated) acquired on the masonry wall, visualized with a false-color palette

2.3. Processing Workflow

In the first phase of the processing workflow, the obtained (single-channel) 32-bit thermal images were downscaled to 16-bit to ensure compatibility with Structure-from-Motion (SfM) photogrammetry software (Agisoft Metashape Professional, which did not allow importing the 32-bit images directly). This procedure was conducted in QGIS software, which allowed for the conversion of the image format without loss of information. Manual tie points (e.g., window corners, façade edges) were selected in both RGB and thermal images to allow for simultaneous camera pose estimation of both datasets in the SfM software.

To account for thermal image distortion and lower contrast, tie-point placement required the use of enhanced contrast filters and histogram stretching. Despite the resolution disparity, the SfM software achieved an average reprojection error of 1.1 pixels, and all the imagery data (both RGB and thermal) was successfully oriented. Using the laser scan point cloud, ten ground control points (GCPs) were extracted and manually matched with image-derived points. Bundle adjustment refined the internal orientation and yielded a model-scale RMSE of 2.1 mm, validating the alignment and ensuring spatial coherence across all datasets, as well as being coherent with the laser scanner accuracy.

To ensure geometrical detail and robustness, dense point cloud reconstruction was based solely on RGB imagery to preserve geometric fidelity by “deactivating” the aligned thermal images while performing this step. The initial cloud (~0.5 mm spacing, Fig. 5) was resampled to 1 mm average spacing to match the thermal image resolution. This compromise maintained sufficient geometric detail while ensuring color mapping with thermograms did not introduce artifacts or interpolation.

Figure 5. RGB dense point cloud obtained with close-range photogrammetry

For the next step of point-cloud colorization, the RGB images were disabled, and only the aligned thermograms were kept active. Because the thermograms were imported as single-channel, 16-bit radiometric images (one pixel value = temperature), the software projected each 3D point into the thermal image plane(s) using the previously solved camera poses and sampled the corresponding pixel value. No pseudo-color mapping or histogram normalization was applied; the native radiometric value (°C) was written as a single-channel attribute per point. The resulting dataset is a thermal point cloud in which each point stores its 3D coordinates and the corresponding temperature—i.e., (X, Y, Z, T), where T is in °C. (Fig. 6).

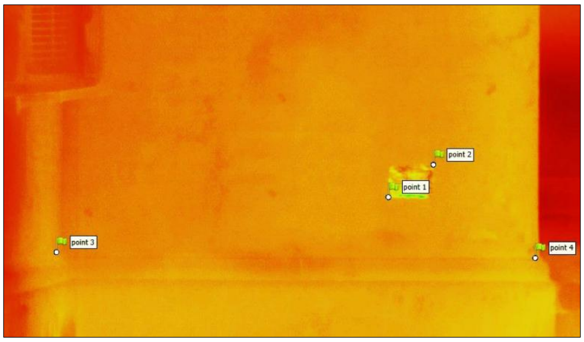

Figure 6. The "thermal" point cloud obtained, with thermal information visualized with a false-color palette. Some of the control points used for SfM are also visible

III. RESULTS AND DISCUSSION

The final output consisted of a spatially aware and thermally calibrated point cloud of ~3.5 million points, each associated with a temperature value. This thermal point cloud enabled both qualitative visualization (through false-color or grey-level mapping, Fig. 7) and quantitative analysis (e.g., by individual point queries or application of threshold filters).

Moreover, the high level of detail achieved through close-range photogrammetric reconstruction enabled both the quantitative assessment of affected areas—by measuring biodegradation patches—and the morphological analysis of the wall surface. These morphological observations can be then correlated with insights from the thermal analysis (Fig. 8)

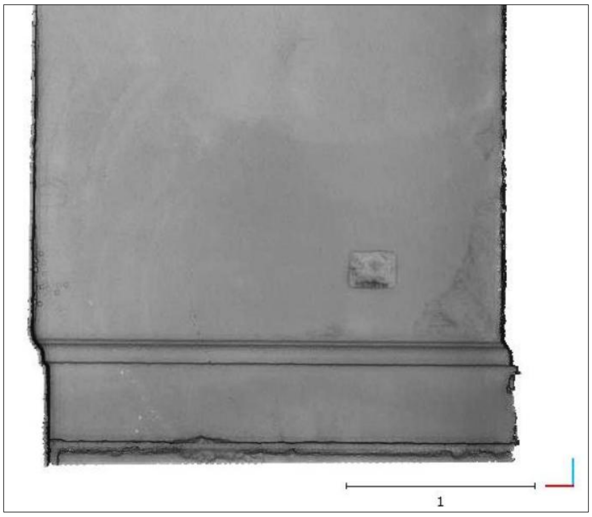

Figure 7. The thermal point cloud, with thermal information visualized as grey levels

Visual inspection revealed a possible correlation between higher temperature zones and known deterioration markers, including biological growth and cracked mortar joints. Cooler zones were associated with moisture-retentive surfaces (e.g., shaded areas, plaster inlets), as confirmed via in situ observations, but require further validation and implementation through future collaboration with materials degradation experts.

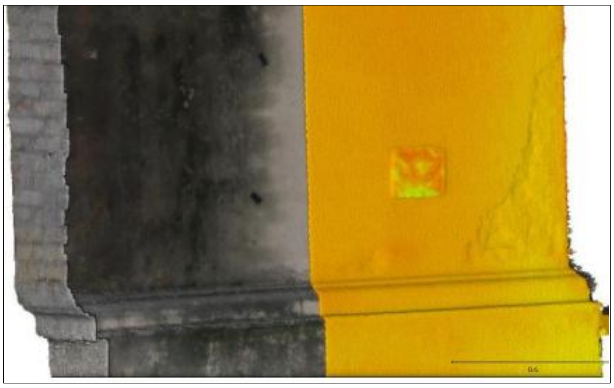

Figure 8. The RGB high-detail 3D point cloud next to its thermal counterpart

Temperature filtering (e.g., isolating all points within specific temperature ranges) highlighted potential zones of moisture accumulation. This provided potential insights into identifying risk areas that may be prioritized in maintenance planning. Moreover, scalar temperature histograms and single values querying on individual points (Fig. 9) helped characterize the thermal behavior of the masonry and building materials more punctually.

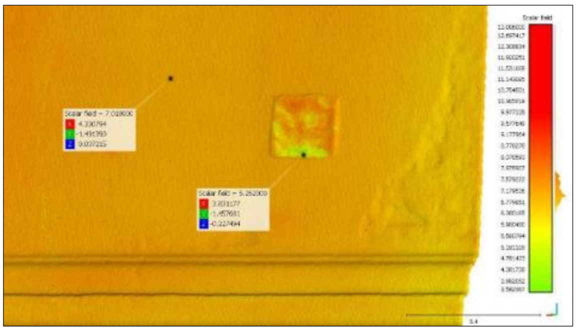

Figure 9. Details of the thermal point cloud showing the querying of individual points associated temperature values

Nonetheless, the thermal analysis conducted did not lead to highly notable results, not underscoring significant temperature variations in proximity to the mosses and biological deterioration, as one could expect. That said, the presented methodology is reported in this article to highlight the potential of numerically integrating thermal investigation with high-detail 3D surveying, which, as described, may bring numerous advantages with respect to visual and qualitative integration. These advantages will be further evaluated in other case studies, where the thermographic analysis may be more valuable and helpful from a heritage conservation perspective.

From a methodological perspective, the principal limitations observed were related to thermal image resolution and manual tie-point matching. The thermal camera pixel size (~0.7 mm at 5 m) was the bottleneck in resolution matching. In addition, alignment quality heavily depended on the operator's ability to identify shared features across different spectral datasets.

A further limitation concerns the absence of information on the internal room temperature, which prevented us from assessing potential temperature gradients between the inner and outer environments, potentially influencing the visibility and interpretation of thermal anomalies. Future improvements may therefore include not only automated or semi-automated feature extraction—e.g., deep learning-based key point identification or the use of coded targets recognizable across multi-spectral datasets—but also the systematic acquisition of both external and internal temperature to better contextualize the thermal analysis.

IV. CONCLUSIONS AND FUTURE PERSPECTIVES

In conclusion, this study presented a complete and replicable workflow for creating a numerically integrated thermal point cloud by combining infrared thermography, photogrammetry, and TLS. Unlike previous techniques that visually map temperature as textures, the described approach embeds thermal values as scalar fields into spatial data, enabling accurate 3D thermographic analysis.

The methodology achieved satisfactory spatial and thermal accuracy, with reprojection errors (~1.1 pixels) and ground control points RMSE (~2 mm) within acceptable limits. The result is a data-enriched model capable of visualizing and analyzing building diagnostics in a spatially aware manner, with a high level of geometrical detail.

Beyond its immediate application in thermal diagnostics and heritage conservation, this integrated approach represents a significant advancement in the field of reality-based modeling. By embedding quantitative thermal data into geometrically accurate models, it becomes possible to analyze and simulate deterioration phenomena, energy performance, moisture ingress, and material behavior in ways that were previously constrained to isolated datasets or two-dimensional thermal maps. Furthermore, this methodology enhances interdisciplinary workflows, bridging the gap between engineering surveys, conservation science, and building performance assessment.

The potential to merge high-resolution geometric data with thermal and spectral information opens opportunities for novel applications, such as predictive modeling of decay processes, automated damage classification, and quantitative assessment of thermal bridges in complex structures. Such developments would significantly improve inspection efficiency, documentation reliability, and decision-making processes in conservation, structural health monitoring, and preventive maintenance.

Future developments of this work (still ongoing) have already been discussed in previous sections, but further steps may include:

- Integration with Building Information Modeling (BIM) platforms for collaborative conservation projects;
- Use in temporal monitoring (time-series thermal point clouds) to detect evolving deterioration issues;
- Integration of multi- or hyperspectral imaging (Fig. 10) into the pipeline to allow the creation of a multiple bands 3D dataset.

Finally, as digital heritage documentation, thermal diagnostics, and spectral analysis continue to evolve, implementing these integrated and data-rich methods at scale will not only improve conservation and monitoring strategies but also set new standards for sustainable management, preventive maintenance, and evidence-based decision-making in both heritage and contemporary built environments. The approach presented here thus can form a foundation for the future strategies in heritage 3D diagnostics, where geometry, material behavior, and thermal dynamics are seamlessly integrated to support comprehensive assets management and monitoring.

Figure 10. Work in progress: performing hyperspectral imaging on the masonry wall portion

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