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From Thermal Signatures to Conservation Insights: A Fixed Camera Network Approach for Heritage Structure Health Monitoring

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***Abstract* – Heritage masonry structures face increasing deterioration risks that require continuous monitoring to enable timely conservation interventions, yet current thermal assessment methods rely on periodic surveys that fail to capture dynamic thermal behaviour patterns. This study presents the implementation of a continuous thermal monitoring system using three fixed infrared cameras (Mobotix M73) for 24/7 monitoring of historic wall sections in Rome. Thermal images acquired at 30-minute intervals were processed using custom-developed algorithms for temporal series extraction, edge detection analysis, and master-slave image comparison to characterize thermal signatures and identify structural anomalies. Results demonstrate distinct thermal behaviour patterns across monitored sections depending on material composition and structural characteristics. Edge detection successfully identified thermal discontinuities corresponding to documented structural fractures and material interfaces, while comparative analysis revealed spatial heating heterogeneity indicative of conservation state variations. The correlation between thermal signatures and known structural vulnerabilities validates continuous thermal monitoring as a non-invasive early warning system for heritage deterioration processes, offering significant potential for preventive conservation strategies and real-time structural health assessment of cultural heritage assets.**

I. INTRODUCTION

Cultural heritage preservation represents one of the most pressing challenges in contemporary conservation science, as historic structures face increasing threats from environmental degradation, climate change, and anthropogenic factors [1]. Ancient masonry structures, particularly those of archaeological significance such as historical city walls and fortifications, are especially vulnerable due to their age, material composition, and exposure to environmental stresses [2]. Traditional inspection methods for assessing structural integrity and detecting early signs of deterioration often rely on periodic visual surveys and localized invasive testing, which may fail to capture the dynamic thermal behaviour of these complex structures and can potentially damage the heritage fabric [3,4].

Current approaches to heritage monitoring predominantly employ conventional non-destructive testing techniques including ground-penetrating radar, ultrasonic testing, and periodic photogrammetric surveys [1,2,5,6]. While infrared thermography has been successfully applied to heritage diagnostics, most implementations have focused on single-point-in-time assessments or short-term campaigns using portable thermal cameras [7,8]. Recent advances in remote sensing technologies have demonstrated the potential for continuous monitoring using satellite-based thermal sensors and drone-mounted thermal imaging systems [9,10]. However, existing methodologies typically lack the temporal resolution and spatial precision necessary to capture diurnal thermal cycles and detect subtle temperature variations that may indicate structural anomalies or material deterioration processes. A significant limitation in current thermal monitoring approaches is the absence of long-term, high-resolution temporal datasets that can reveal the complex thermal behaviour patterns of heritage masonry structures.

This paper demonstrates the implementation and preliminary results of a novel continuous thermal monitoring system for heritage wall structures using fixed infrared thermal cameras with automated data acquisition and advanced image processing capabilities. The study presents the installation of three Mobotix M73 thermal cameras for 24/7 monitoring of selected sections of Aurelian walls, operating since January 2025. The research scope encompasses the development of specialized data processing workflows using the custom-developed *Thermal Digger* software [11] for extracting temporal thermal series, implementing edge detection algorithms for identifying thermal discontinuities, and performing master-slave image comparison analysis to characterize thermal behaviour patterns. The contribution includes both the technical implementation of a scalable continuous thermal monitoring system and the analytical framework for processing multi-temporal thermal data to support heritage conservation decision-making.

II. MATERIALS & METHODS

A. Monitoring Sites and Structural Characteristics

Three distinct wall sections of the historic Aurealian Walls were selected for continuous thermal monitoring based on their representative structural characteristics and accessibility for instrumentation installation (Figure 1). The monitored sections include: (1) Section M 14-15 located at the Academy of Fine Arts of Rome, representing typical masonry construction with documented structural fractures; (2) Section L 21-22 at Largo Chiarini, characterized by heterogeneous construction materials from different historical periods and restoration interventions; and (3) Tower L 16 at Viale di Porta Ardeatina, representing a preserved tower structure with rectangular geometry and varying conservation states. Each section exhibits different material compositions, structural configurations, and exposure conditions, providing a comprehensive dataset for thermal behavior analysis across varying heritage masonry typologies, which are expected to be related to different thermal conductivity and sunlight absorption properties.

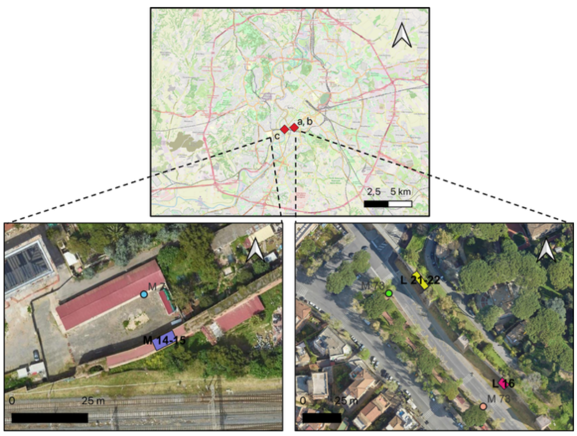


Fig. 1. Sections of the historic Aurelian Walls being monitored with thermal cameras. (a) L 21-22; (b) L 16; (c) M 14-15.

B. Thermal Imaging Equipment

Continuous thermal monitoring was implemented using three Mobotix M73 thermal cameras (Figure 2). The cameras operate in the long-wave infrared spectrum (7.5 to 13.5 µm) with a thermal sensitivity of 50 mK and a measurement range from -40°C to +550°C. Thermal images are acquired at 336×252 pixel resolution with an automated acquisition interval of 30 minutes, providing continuous 24-hour monitoring capability. Camera installations were strategically positioned to optimize thermal monitoring coverage while minimizing visual impact on the historic environment. The Section M 14-15 camera was mounted between the roof and window opening of the adjacent building, providing direct line-of-sight to the wall structure. Cameras monitoring Section L 21-22 and Tower L 16 were anchored to existing street lighting infrastructure along with Remote Access Controllers (RAC) for power management and data synchronization. This approach leveraged existing urban infrastructure while maintaining appropriate monitoring distances and viewing angles for comprehensive thermal coverage of the target structures.

Fig. 2. Mobotix M73 equipped with both thermal infrared and optical sensors (left); RAC system and thermal camera monitoring the Section L 21-22 (right).

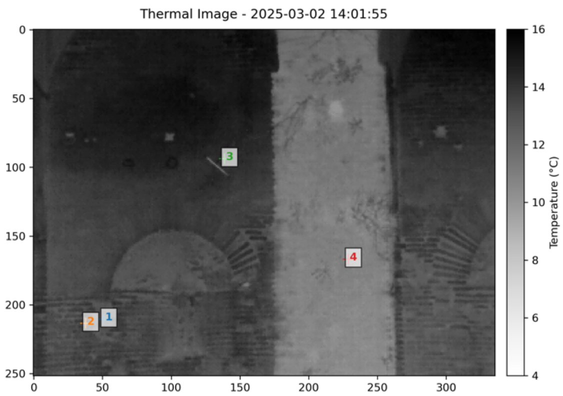
C. Data Acquisition and Processing

Thermal data transmission and archival were implemented through a centralized QNAP remote storage system synchronized with dedicated cloud services, enabling real-time data access and backup redundancy. Raw thermal image extraction utilized the Mobotix SDK EventStream application [12] to convert proprietary thermal image formats into numerical CSV matrices containing temperature values for each pixel. This conversion process preserves the quantitative thermal data necessary for detailed temporal analysis while maintaining compatibility with custom processing algorithms. Multi-temporal thermal analysis was conducted using the custom-developed "Thermal Digger" software [11], a Python-based application designed specifically for extracting temporal thermal signatures from continuous thermal imaging datasets. The processing workflow encompasses three primary analytical approaches: (1) point-based and area-based time series extraction for quantitative temperature tracking; (2) edge detection algorithms using gradient-based methods to identify thermal discontinuities and structural interfaces; and (3) master-slave image comparison analysis for characterizing differential thermal responses during heating and cooling cycles. Temperature parameters monitored include absolute temperature values in degrees Celsius, thermal gradients with variable sliding window calculations applied to both time series and spatial image data, and edge detection gradients for identifying high thermal contrast zones.

III. Results and Discussion

A. Section M 14-15 Thermal Response

Thermal analysis of the Academy of Fine Arts wall section reveals diurnal temperature oscillations with approximately 10°C amplitude during the monitored period (Figure 3). Point-based temporal series extraction from strategically positioned monitoring locations shows differential thermal behaviour between structural elements, with the foreground column exhibiting consistently lower temperatures and reduced thermal excursions compared to interior wall portions. Edge detection analysis successfully identified thermal discontinuities corresponding to documented structural fractures, with enhanced thermal contrasts appearing along crack boundaries (Figure 4). Master-slave image comparison between daily temperature extremes (06:31 vs 12:02 on March 4, 2025) demonstrates non-uniform heating patterns, with the upper portion of the monitored area experiencing more pronounced thermal variations compared to lower sections (Figure 5). Notably, the documented structural fracture under geotechnical monitoring exhibits distinct thermal signatures that may influence crack evolution processes.



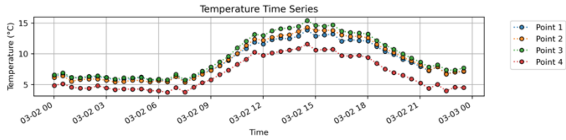


Fig. 3. Thermal image of Section M 14-15 (top) with highlighted the monitored points related to the time series plot (bottom).

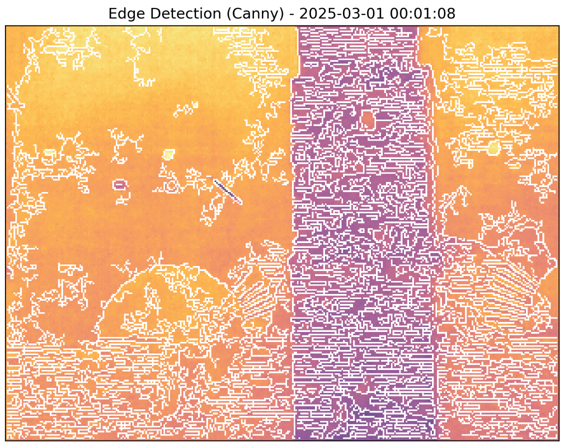


Fig. 4. Thermal image with detected thermal edges shown by white vectors.

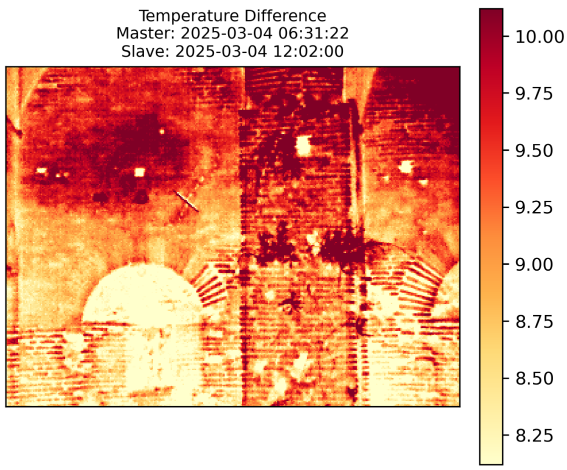


Fig. 5. Master-slave image comparison with resulting pixel-wide temperature differences.

B. Section L 21-22 Multi-Material Thermal Analysis

The Largo Chiarini wall section, characterized by heterogeneous construction materials from different historical periods (sections in brickwork from the Aurelian-Honorian period (271–403 AD) and segments in mixed masonry with flakes of flint, tuff, and peperino stone (12th–13th centuries), displays the most pronounced thermal variations with maximum diurnal oscillations reaching 40°C for most monitoring points. However, Point 3, representative of alternative construction material, demonstrates significantly reduced thermal excursions (24°C), confirming the influence of material thermal properties on structural thermal response (Figure 6). Edge detection processing reveals distinct thermal boundaries between different construction phases, with steel reinforcement elements in the upper section and material interfaces clearly delineated through thermal contrast mapping (Figure 7). The upper section exhibits broader, less dense edge patterns suggesting more homogeneous thermal distribution, while the lower portion shows dense edge networks indicative of highly fragmented thermal texture. Master-slave comparison analysis (07:00 vs 13:00 on April 5, 2025) quantifies spatial heating heterogeneity, with differential thermal responses directly attributable to varying material thermal properties across the wall section (Figure 8).

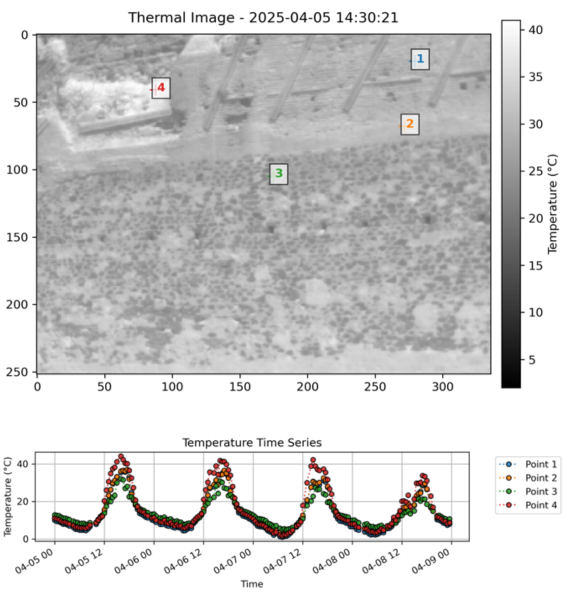


Fig. 6. Thermal image of Section L 21-22 (top) with highlighted the monitored points related to the time series plot (bottom).

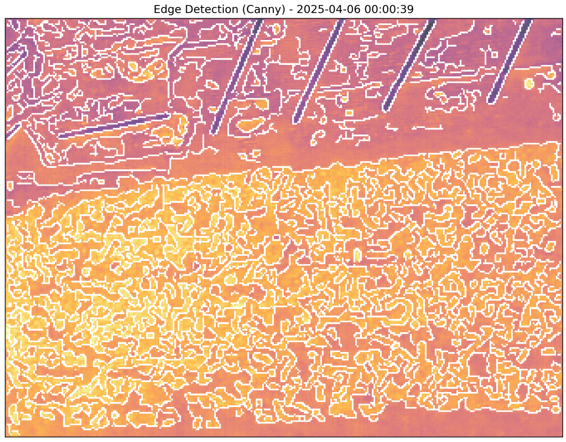


Fig. 7. Thermal image with detected thermal edges shown by white vectors.

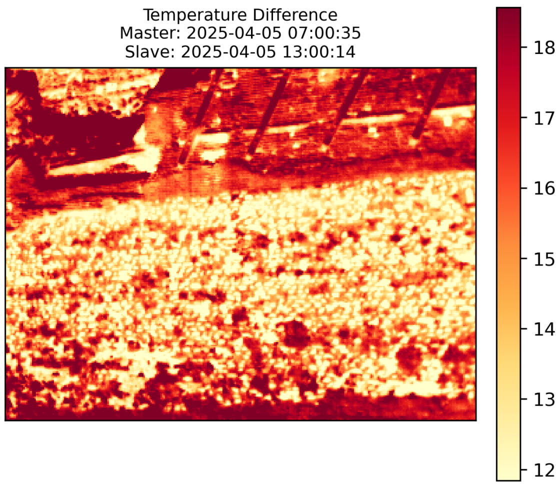


Fig. 8. Master-slave image comparison with resulting pixel-wide temperature differences.

C. Tower L 16 Thermal Signature Analysis

Thermal monitoring of the tower structure reveals extreme temperature ranges with minimum values near 2°C and maximum temperatures reaching 50°C, demonstrating the most significant thermal excursions among monitored sections (Figure 9). Statistical analysis of polygonal area extraction shows substantial differences between minimum and maximum temperature evolution patterns, indicating non-uniform thermal distribution within the structure. Edge detection analysis clearly delineates the rectangular tower geometry with well-defined vertical boundaries on the eastern facade, while complex edge patterns in vegetation-free areas suggest multiple thermal discontinuities potentially related to conservation state variations (Figure 10). Comparative thermal analysis between daily extremes (06:31 vs 15:01 on April 5, 2025) reveals heterogeneous heating and cooling processes, with distinct horizontal striations in the lower tower section potentially indicating structural heterogeneities or differential conservation states (Figure 11).

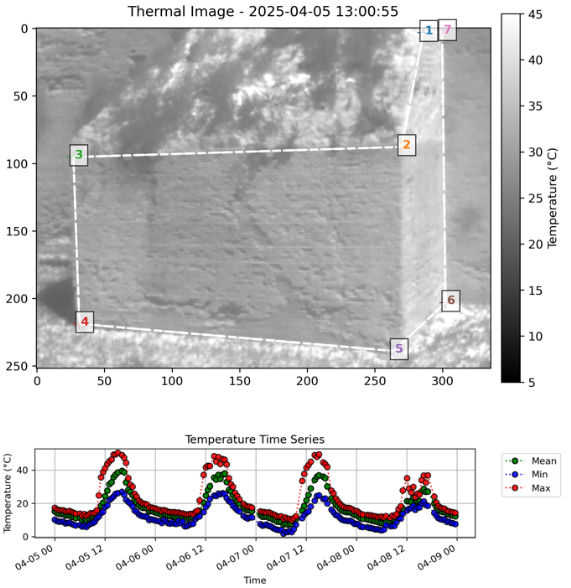


Fig. 9. Thermal image of the Tower L 16(top) with highlighted the monitored points related to the time series plot (bottom).

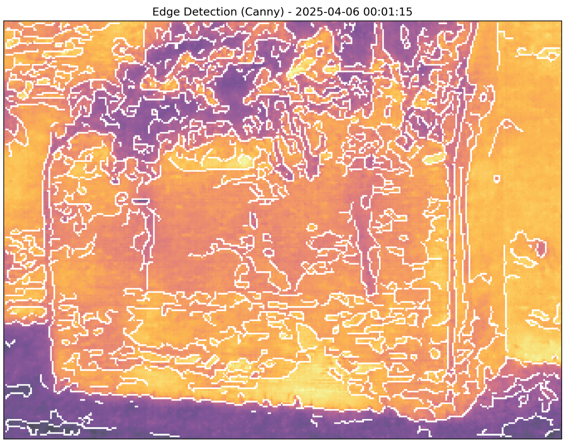


Fig. 10. Thermal image with detected thermal edges shown by white vectors.

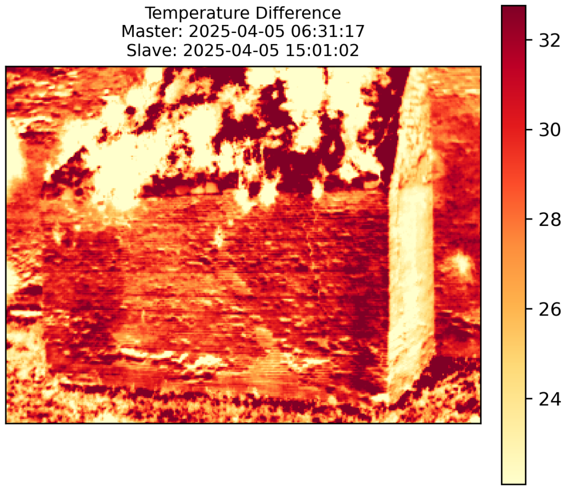


Fig. 11. Master-slave image comparison with resulting pixel-wide temperature differences.

D. Thermal Pattern Interpretation and Structural Implications

The multi-temporal thermal analysis demonstrates clear correlations between structural characteristics and thermal response patterns. Thermal discontinuities identified through edge detection consistently correspond to documented structural features including fractures, material interfaces, and construction joints. The differential thermal responses observed during daily heating-cooling cycles provide quantitative indicators of material heterogeneity and potential degradation zones. Significantly, areas exhibiting anomalous thermal behaviour patterns align with known structural vulnerabilities, suggesting that continuous thermal monitoring can serve as an early warning system for progressive deterioration processes. The integration of point-based temporal analysis, spatial edge detection, and comparative thermal mapping provides a comprehensive framework for characterizing heritage structure thermal signatures and identifying areas requiring focused conservation attention.

IV. Conclusion

This study demonstrates the successful implementation of a continuous thermal monitoring system for heritage masonry structures using fixed infrared cameras with automated data acquisition and advanced processing algorithms. The research addresses critical gaps in heritage conservation monitoring by providing high-resolution temporal thermal datasets that enable detection of structural anomalies and material deterioration processes through quantitative thermal signature analysis. The developed methodology integrates continuous thermal imaging with specialized data processing workflows to characterize the complex thermal behaviour of historic wall structures, offering a scalable approach for long-term heritage monitoring applications. The installation and operation of three Mobotix M73 thermal cameras across representative wall sections of Aurelian Walls has generated comprehensive multi-temporal datasets since January 2025. Analysis revealed distinct thermal signatures for each monitored section, with diurnal temperature variations ranging from 10°C to 40°C depending on structural characteristics and material composition. Edge detection algorithms successfully identified thermal discontinuities corresponding to documented structural features including fractures, material interfaces, and construction joints. Master-slave image comparison analysis quantified differential thermal responses during heating-cooling cycles, revealing spatial patterns of thermal heterogeneity that correlate with known structural vulnerabilities. The findings establish continuous thermal monitoring as a viable non-invasive approach for heritage structure health assessment, with implications for preventive conservation strategies and early warning systems for structural deterioration. The demonstrated correlation between thermal signatures and structural characteristics validates the potential for thermal monitoring to complement traditional heritage conservation assessment methods.

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