Chapter

# Thermography Applied to Old Masonry Constructions

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## Abstract

Infrared thermography is a non-invasive technique widely used in architectural heritage conservation to analyze surface temperatures and identify material deterioration. This study presents the application of both terrestrial and aerial thermography for diagnosing structural pathologies in historical monuments. Thermographic imaging facilitates the detection of hidden elements, moisture infiltration, thermal bridges, and material heterogeneities without physical contact. The research examines case studies such as the Tower of Hercules and La Giralda, demonstrating the advantages of drone-mounted cameras for capturing hard-to-reach areas. Results confirm the effectiveness of thermography in recognizing material differences, moisture-induced damage, and the influence of environmental conditions on historical structures. The findings emphasize the importance of optimizing thermal camera parameters and selecting appropriate environmental conditions to enhance measurement accuracy. The study concludes that the combined use of terrestrial and aerial thermography provides valuable insights for preventive conservation strategies, contributing to the preservation of cultural heritage through non-destructive methods.


**Keywords:** thermography, heritage conservation, aerial inspection, infrared imaging, structural pathology

## 1. Introduction

Thermography is a recognition technique based on the detection of radiation emitted by objects, converting the captured information into images that provide highly valuable data regarding the surface temperature of the photographed bodies. Its significance is such that it has not only become a subject of detailed study in the field of heritage and historical constructions [1], but it is also currently regarded as a fundamental instrumental inspection technique in the field of monument conservation.

A conventional photographic camera, like the ones integrated into most modern smartphones, detects the visible light emitted by objects, capturing this visible light on a medium to produce photographs that can be easily perceived by the human eye. In other words, a photographic camera detects visible light and records it in a photograph. In contrast, a thermal camera detects infrared emissions: infrared radiation has a lower frequency than visible light, which makes it undetectable to the human eye. However, infrared radiation can be perceived organoleptically as heat. While the human eye is insensitive to the infrared radiation emitted by objects, the skin can


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detect it. Therefore, a thermal camera captures the surface temperature of objects and records it in the form of a thermal image (or thermogram).

The reduction in camera costs over recent years, combined with their integration into drones as an additional component, has paved the way for a new, highly useful microtechnology that can be leveraged for the inspection of monuments and their constituent materials. For this reason, the following sections will analyze the potential applications of this technology in the context of heritage conservation.

## 2. Objectives

The objectives of the research included in this chapter are the following:

1. To analyze the potential of terrestrial and aerial thermography in the conservation of architectural heritage through non-invasive techniques.

2. To identify material damage and structural pathologies in historical constructions using thermal imaging technology.

3. To assess the effectiveness of infrared thermography in detecting hidden structural elements, moisture infiltration, and thermal anomalies.

4. To propose guidelines for the standardized application of thermography in preventive conservation practices for heritage structures.

## 3. Methodology

The methodology of this study follows a systematic approach to apply and evaluate terrestrial and aerial thermography in the context of architectural heritage conservation. The research was conducted in multiple historical monuments, utilizing thermal imaging techniques to identify material heterogeneities, moisture infiltration, and potential structural pathologies.

The study employs a descriptive and diagnostic research design to assess the thermal behavior of various heritage structures. The design integrates both qualitative observations and quantitative thermal measurements to identify patterns indicative of deterioration processes.

The methodology was applied to a series of historical monuments, including the Tower of Hercules, La Giralda, and the Cathedral of León. These case studies provided empirical evidence of thermography's effectiveness in detecting structural irregularities and evaluating material performance.

This methodological approach underscores the potential of terrestrial and aerial thermography as a non-invasive, reliable tool for the preservation of architectural heritage, offering critical insights into the thermal behavior and structural integrity of historical constructions.

## 4. Fundamentals of thermography

Conventional photographic cameras detect the visible light emitted by objects and are capable of capturing this visible light in a photograph. In contrast, thermal cameras perform a similar task with infrared emissions. Infrared radiation has a lower frequency than visible light, which makes it undetectable to the human eye. However, infrared radiation can be perceived organoleptically as heat. While the human eye is insensitive to the infrared radiation emitted by an object, human skin can detect it. Thus, a thermal camera records the surface temperature of objects as a thermal image.

Depending on the camera model, some thermal cameras can detect temperature differences as small as a few hundredths of a degree. Thermography is an instrumental diagnostic and inspection technique of significant interest in the study of heritage materials [2]. It allows for the precise measurement of surface temperatures [3] without requiring physical contact with the object.

The primary characteristics of thermography are as follows [4]:

- It is non-invasive and operates remotely.
- It captures the observed object within an image, enabling temperature analysis.
- It allows for rapid visualization of stationary objects.
- The images provide information about temperature distribution, thermal patterns, behavior, and any existing anomalies.

Thermal images are commonly used to identify so-called 'hot spots'—points on an object where the temperature is higher, making them stand out in the thermal image or thermogram. For instance, the author of this study has employed thermography to locate buried structural metallic elements (**Figure 1**) or concealed utility pipelines (**Figure 2**). Infrared thermography is essential for accurately assessing the condition of building envelopes, as it facilitates the detection of thermal bridges, insulation

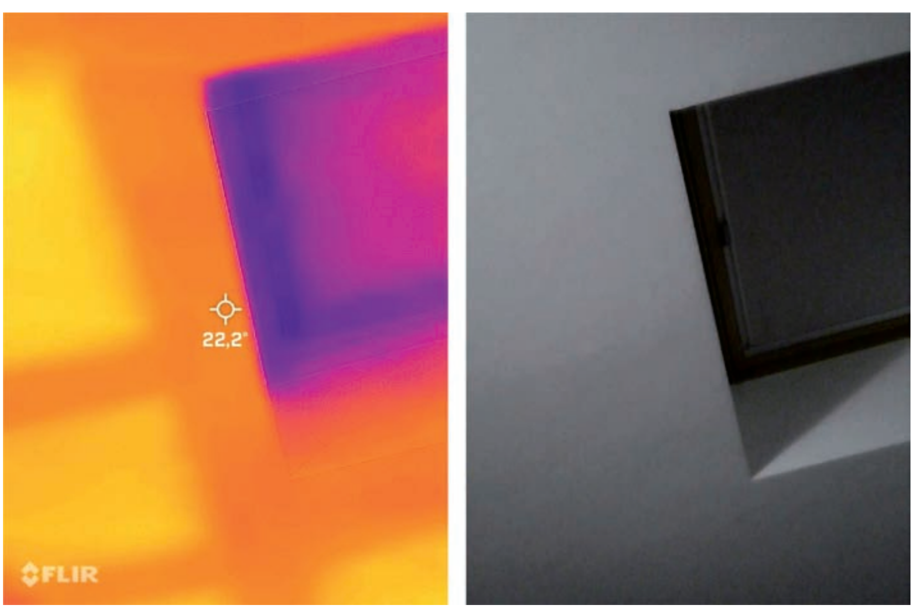


**Figure 1.**
*Thermal analysis of an attic residence, illustrating the location of hidden beams, structural elements, and heat losses near the skylight (images by the author).*

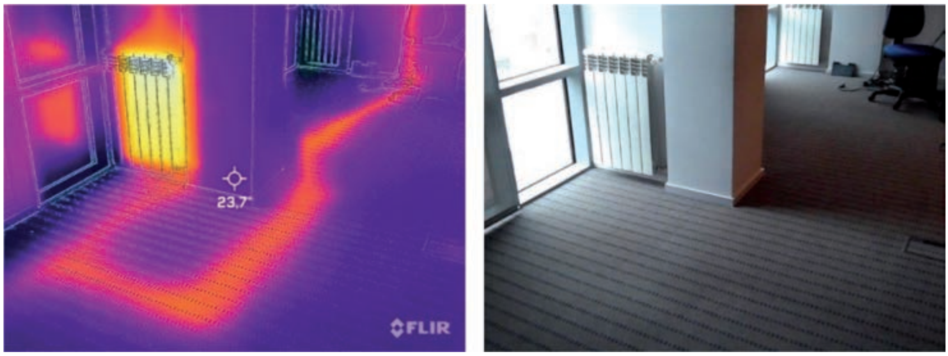


**Figure 2.**
*Detection of an active heat conduction pipe supplying a radiator in an office building (images by the author).*

defects, moisture intrusions, and other building pathologies [5]. This makes thermography particularly valuable for heritage inspection applications.

As mentioned in the introduction, thermography is a technique based on detecting the radiation emitted by objects and converting this information into images that reveal surface temperature data. Any object with a temperature above absolute zero (0 Kelvin = −273.15°C) emits infrared radiation (IR radiation). The human eye cannot perceive this radiation because it is insensitive to infrared wavelengths (**Figure 3**). However, the core component of a thermal camera—the infrared detector—is sensitive to this radiation. By analyzing the intensity of the infrared radiation, the detector determines the object's surface temperature and converts it into a thermal image that the human eye can interpret. This process is known as thermography.

To make infrared radiation visible, the detector captures the radiation, converts it into an electrical signal, and assigns each signal a specific color displayed on the thermal camera's screen. In simpler terms, a thermal camera translates infrared wavelengths into visible wavelengths, producing a color-coded image.

Contrary to popular belief, thermal cameras do not allow users to see inside objects; they only visualize surface temperature. However, if an internal object has a significantly different temperature, this temperature discrepancy may become visible in the thermal image (**Figures 1** and **2**).

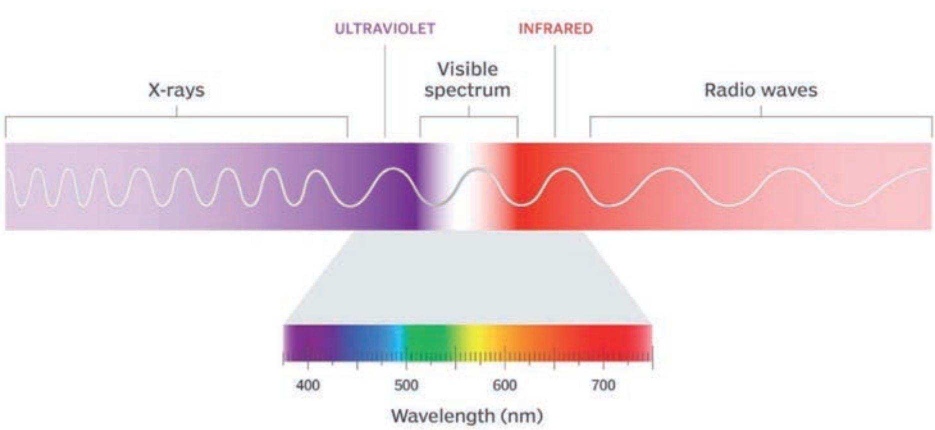


**Figure 3.**
*Visible and invisible light (graphic by Scarpatti [6]).*

The radiation detected by a thermal camera consists of three components: emitted, reflected, and transmitted radiation [7], originating from objects within the camera's field of view (**Figure 4**).

- Transmission (τ): Transmission refers to a material's ability to allow infrared radiation to pass through it. For instance, a thin plastic sheet exhibits high transmissivity. Consequently, if a thermal camera is used to measure the temperature of a plastic sheet placed in front of a building facade, the measurement will reflect the facade's temperature rather than that of the plastic. Most materials, however, do not transmit infrared radiation, meaning their transmissivity is close to zero and can be disregarded in practical applications.

- Emission (ε). Emission describes a material's capacity to emit infrared radiation and is expressed as a percentage. This property depends on the material's composition and surface characteristics. For example, the sun has an emissivity of 100%. Although this value is rarely encountered in everyday applications, materials like concrete exhibit high emissivity, with values around 93%. This indicates that 93% of the infrared radiation detected originates from the concrete itself.

- Reflection (ρ). Reflection represents the infrared radiation from the surrounding environment that bounces off the object's surface. For instance, if concrete has an emissivity of 93%, the remaining 7% corresponds to reflected radiation. Modern thermal cameras allow users to input both emissivity and reflected temperature values to enhance measurement accuracy.

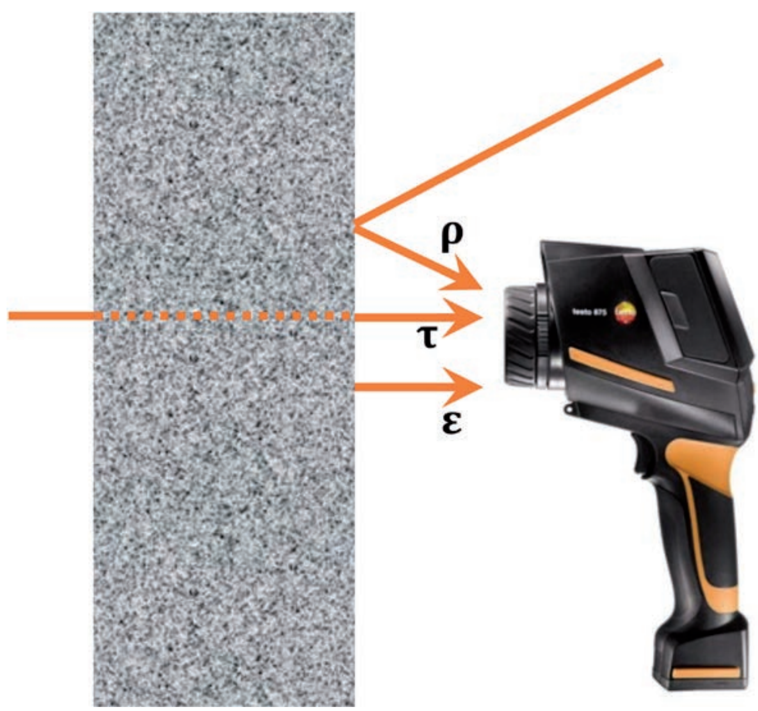


**Figure 4.**
*Emitted (ε), reflected (ρ), and transmitted (τ) radiation recorded by a thermal camera (diagram by the author).*

Thermal cameras generate images in which each pixel corresponds to a specific temperature value. These images typically employ pseudocolor scales, where cooler temperatures are represented in shades of blue and warmer temperatures in shades of red.

Infrared thermography, therefore, stands as a crucial, non-invasive tool for monitoring and analyzing the thermal behavior of historical structures, providing essential data for the diagnosis and conservation of heritage materials.

## 5. Terrestrial thermography applied to architectural heritage

Thermography can be employed as an instrumental technique for diagnosing and inspecting heritage materials of great interest. It can also aid in the characterization of materials of diverse origins when materials with distinct characteristics coexist within the same monument. For instance, the case of the Torre del Oro in Seville illustrates this application. In this structure, limestone blocks from different periods coexist with mortar in the lower part of the monument, presenting, depending on their age and exposure to external agents, a clearly distinguishable appearance to the naked eye (**Figure 5**), which is equally evident in the thermal image captured by the thermographic camera (**Figure 6**).

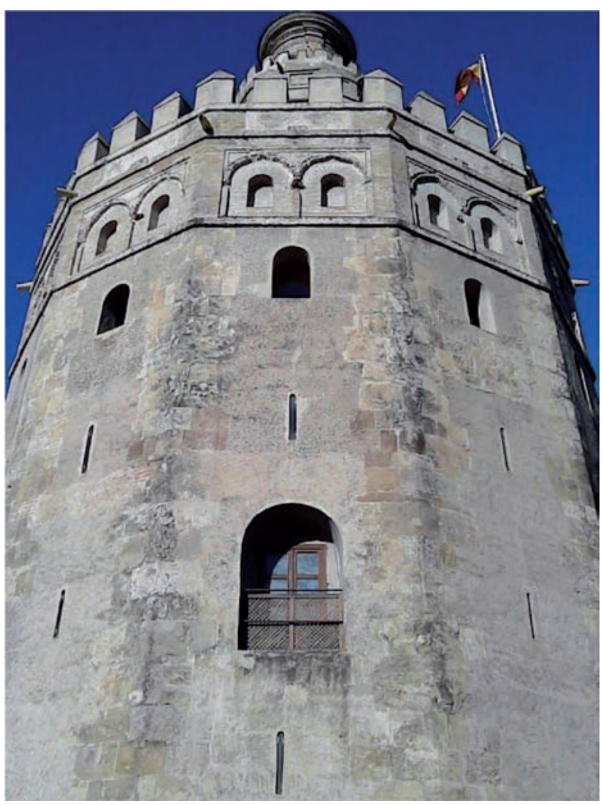

**Figure 5.**
*Photographic image of the southern flank of the Torre del Oro in Seville, next to the Guadalquivir River (photo by the author).*


**Figure 6.**
*Thermogram of the image in* **Figure 5***, clearly showing the different materials used in construction (photo by the author).*

This distinction becomes even more pronounced when dealing with materials of markedly different nature. A clear example can be observed in the entrance door of Girona Cathedral (**Figure 7**), located on its western facade. Amidst the stone ornamentation made of limestone rock, the entrance door, being metallic, displays a stark contrast in the thermogram (**Figure 8**) due to the difference between the sedimentary rock of the facade and the metal of the door.

The Cathedral of León is globally renowned for its stained-glass windows. Beyond their decorative function, these tinted glasses were strategically placed to allow sunlight to illuminate the temple's interior. Consequently, the difference between the limestone of the walls and the glass of the windows is substantial in terms of transmission, emission, and reflection. From the outside, significant differences become apparent in both the photographic image (**Figure 9**) and the corresponding thermogram (**Figure 10**). Particularly interesting in this regard are the thermal readings captured around the edges of the windows.

Thus, the Torre del Oro exemplifies the utility of thermography in differentiating materials of varying ages. However, experience indicates that this observation cannot be universally applied. For instance, the enclosing walls of Palma de Mallorca Cathedral demonstrate this limitation. While a photographic camera can distinguish younger from older Marés sandstone blocks [8] due to differences in color and texture (**Figure 11**), the thermogram reveals this distinction with much less clarity (**Figure 12**). Conversely, in the granite blocks protecting the ancient Roman

**Figure 7.**
*Photographic image of the entrance to Girona Cathedral on its western facade (photo by the author).*

lighthouse of the Tower of Hercules (**Figure 13**) [9], the differentiation is more evident in the thermogram than in the photographic image (**Figure 14**) [10].

Another illustrative example can be found in the lower section of the eastern facade of La Giralda, the bell tower of Seville Cathedral. Despite its recent restoration [11], issues related to the brickwork, particularly moisture problems, persist. These issues are visible to the naked eye in the photograph (**Figure 15**) but become even clearer in the thermographic image, where areas affected by moisture are

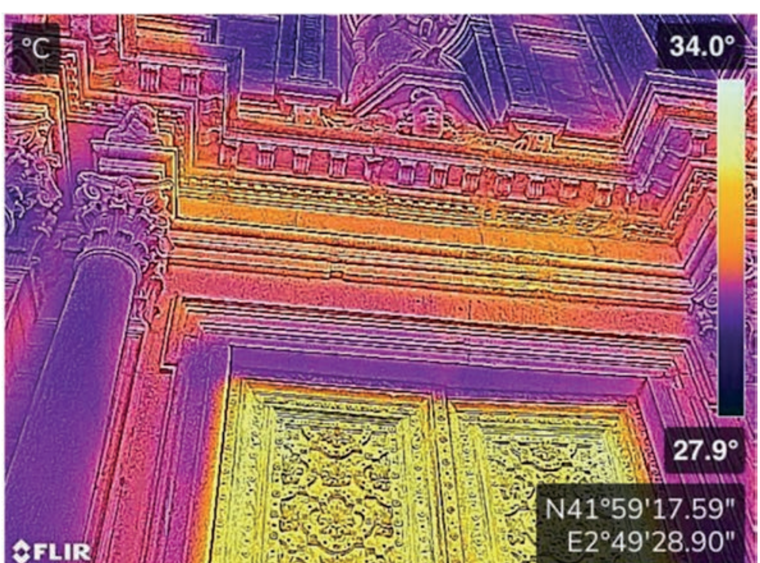


**Figure 8.**
*Thermogram of the image in* **Figure 7***, illustrating the distinct materials (photo by the author).*

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**Figure 9.**
*Photographic image of the eastern apse of León Cathedral (photo by the author).*

distinctly identifiable. Given the operational principles of thermography, it is logical to expect that moist areas would appear warmer than dry ones due to evaporative cooling (**Figure 16**). Nevertheless, this is not always the case, as thermal history can sometimes obscure useful signals, as observed in the lower rows of the bell tower of Valencia Cathedral, the Torre del Miguelete (**Figure 16**). Here, the varied degrees of moisture absorption, resulting from poorly executed restorations with


**Figure 10.**
*Thermogram of the image in* **Figure 9***, highlighting the material differences (photo by the author).*

**Figure 11.**
*Detail of the south façade wall of the Cathedral of Palma de Mallorca, where different ashlars from the Marés can be seen (photo by the author).*

unsuitable materials [3], are accurately detected by the thermographic camera (**Figures 17** and **18**).

Similar phenomena can be observed in the stone blocks of Barcelona Cathedral's facade. The Montjuic sandstone [12] exhibits deterioration caused by the synergistic action of chemical and biological agents, notably the formation of black crusts (**Figure 19**), presumably linked to sulfur compounds from urban pollution [3]. This


**Figure 12.**
*Thermogram of the image in* **Figure 11***, highlighting the material differences (photo by the author).*

**Figure 13.**
*Detail of the granite and mortar components of a section of the Tower of Hercules lighthouse (photo by the author).*

phenomenon is unsurprising given the monument's central location in one of Europe's busiest cities. The restriction of traffic near the Cathedral is relatively recent, considering the building's age. Some of these lesions manifest distinctly in the corresponding thermogram (**Figure 20**).

When biological growth, such as plants, takes root in the joints between blocks, especially at angular points [3], their action exacerbates moisture issues, efflorescence, and runoff stains. These patterns are visible in both the photograph

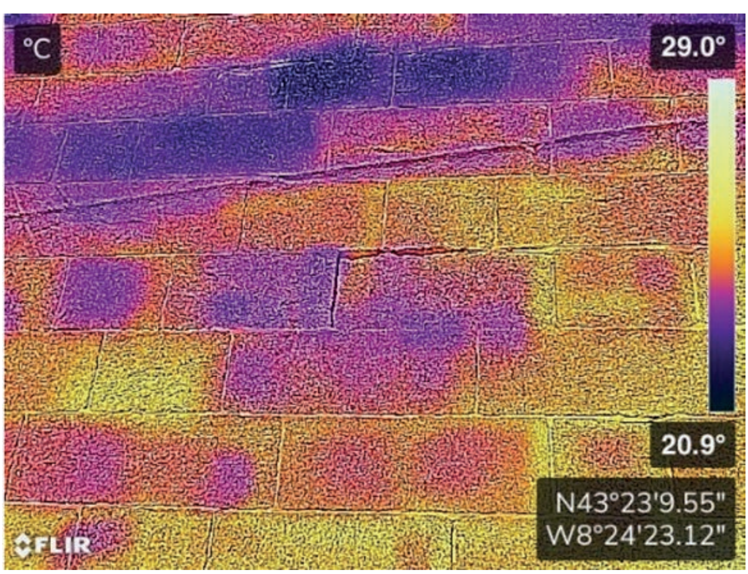


**Figure 14.**
*Thermogram of the image in* **Figure 13***, clearly differentiating the various blocks (photo by the author).*

**Figure 15.**
*Photographic image of the lower eastern facade of La Giralda in Seville Cathedral, revealing moisture issues (photo by the author).*

(**Figure 21**) and thermogram (**Figure 22**) of the western facade of Girona's Basilica of Sant Feliu [13].

The aforementioned examples underscore the utility of ground-based thermography in numerous heritage-related applications, predominantly associated with material durability.

Generally, these damages pertain to material durability rather than structural integrity, meaning they do not pose an immediate threat to the monument's stability but may lead to more severe damage if left unaddressed. Processes such as alveolization or sandstone disintegration can occur as a result [3]. The detection of efflorescence indicates ongoing chemical degradation and suggests the potential development of internal mechanical stresses due to salt crystallization.

In the context of heritage conservation, damage related to material durability stems from the interaction between the deteriorated material and the surrounding environmental conditions. In other words, material durability reflects a material's capacity to withstand environmental factors, including chemical, physical, and biological attacks or any other environmental process contributing to material deterioration.

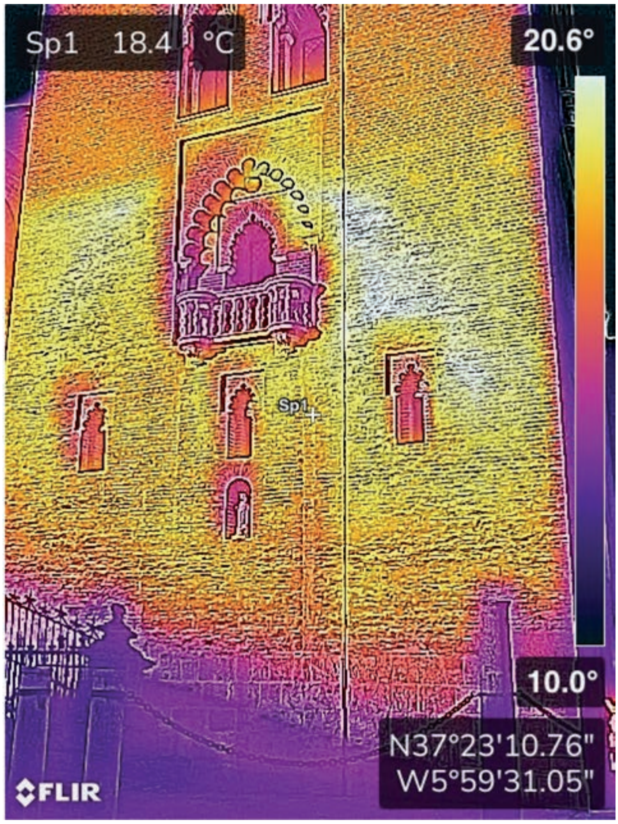


**Figure 16.**
*Thermogram of the image in* **Figure 15***, showing varying moisture levels in the brickwork (photo by the author).*

**Figure 17.**
*Detail of the southeast facade base of the Torre del Miguelete in Valencia Cathedral, showing diverse materials and varying deterioration states (photo by the author).*

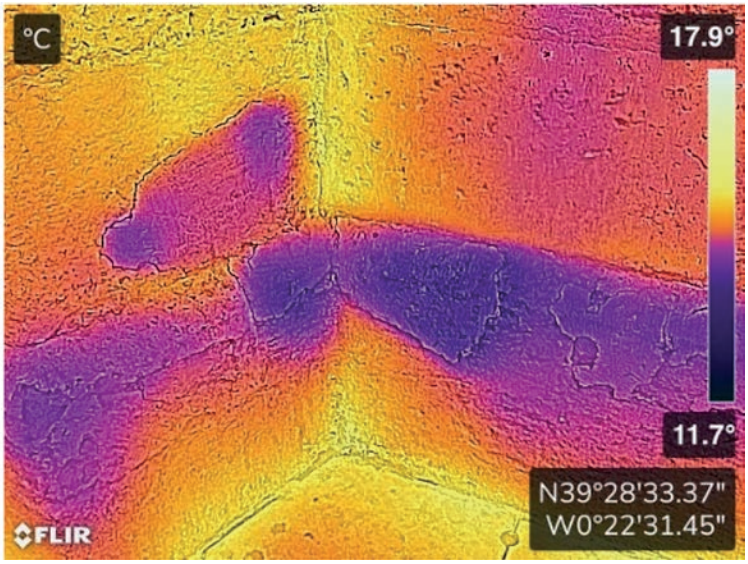


**Figure 18.**
*Thermographic analysis of the materials from* **Figure 17**, *revealing the differences captured by the camera (photo by the author).*

**Figure 19.**
*Black crusts on the sandstone ashlars of the facade of the Cathedral of Barcelona (photo by the author).*

## 6. Aerial thermography applied to architectural heritage

Thermal cameras provide information that cannot be obtained through other types of imaging. However, these cameras often face challenges in achieving optimal positioning for the desired perspective. In this context, drones, with their versatile maneuverability and positioning capabilities, can place thermal cameras in vantage points that are otherwise difficult to access.

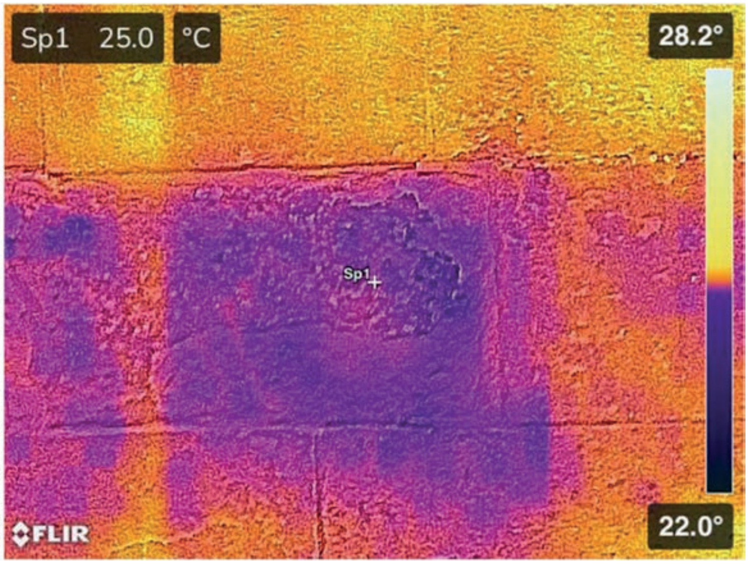


**Figure 20.**
*Thermographic analysis of the ashlars in* **Figure 19***, reflecting the black crusts photographed (photo by the author).*

**Figure 21.**
*Detail of the lower eastern facade of the Basilica of Sant Feliu, with visible vegetation growth (photo by the author).*

Given the compact size and lightweight nature of modern thermal cameras, nearly any multirotor drone can now carry one. This advancement gave rise to aerial thermography: the fusion of thermographic imaging with drone piloting allows for the capture of thermal data from otherwise inaccessible viewpoints. For instance, for the accurate analysis of thermal anomalies, it is recommended that the thermal camera be positioned at an angle of 70 to 90° (**Figure 23**) relative to the surface under inspection

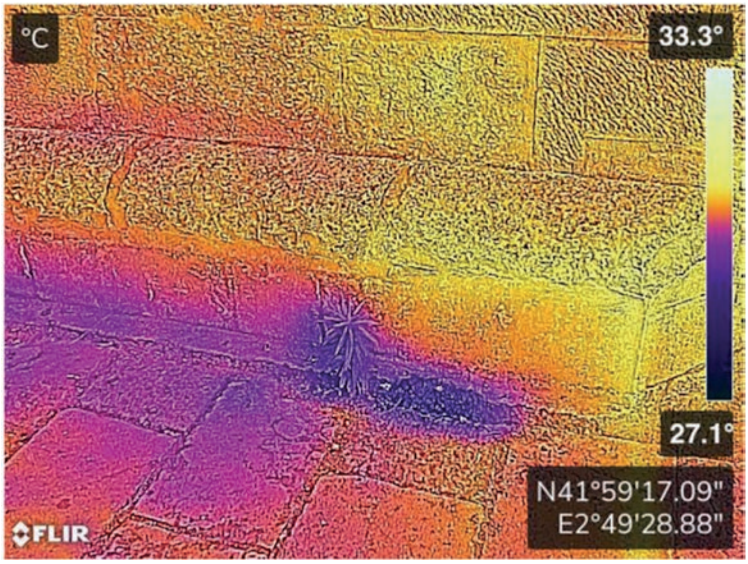


**Figure 22.**
*Thermographic analysis of the image from* **Figure 21***, showing the material differences detected by the camera (photo by the author).*

[14]. Achieving this with a handheld camera is challenging, whereas a drone-mounted thermal camera can accomplish it with ease [15].

The primary limiting factor during thermal measurements is often the meteorological conditions, as these can significantly impact measurement accuracy. As previously mentioned, thermal surveys should ideally be conducted during twilight—either at dawn or dusk—when temperature differences become more pronounced. During these periods, the varying heat dissipation of heterogeneous zones becomes evident, aiding in the identification of structural defects. Optimal conditions for measurements include an ambient temperature of approximately 25°C, solar radiation of 1000 $Wm^{-2}$, and some cloud cover to enhance thermal contrast. Unfortunately, these conditions are not always attainable.

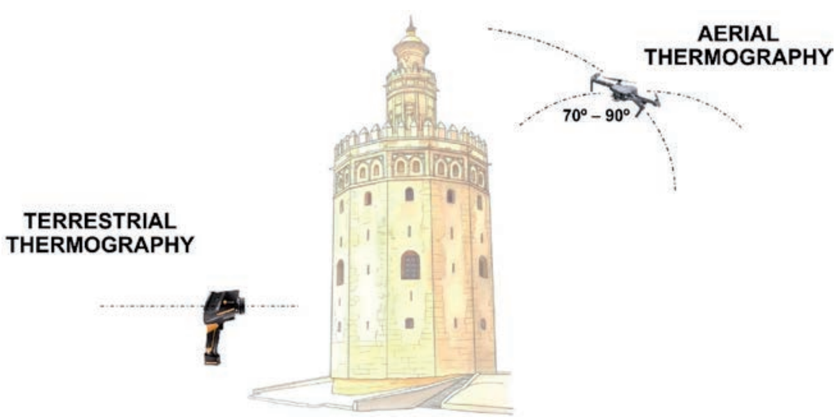


**Figure 23.**
*Comparative analysis of the rigidity of terrestrial thermography and the flexibility of aerial thermography in a hypothetical thermographic inspection of the Torre del Oro (diagram by the author).*

All objects with a surface temperature above absolute zero (0 K or − 273.15°C) emit electromagnetic energy in the infrared spectrum (0.75 to 100 μm). According to Stefan–Boltzmann's law [16], the infrared radiation emitted by an object increases with its temperature. This law applies to ideal black bodies—objects with an emissivity (ε) of approximately 100% [17]. Real objects, however, emit less radiation due to the partial reflection of incident infrared energy.

The total infrared radiation detected by a thermal camera ( $W$ ) can be expressed as:

$$W = \tau\left[\varepsilon\,\sigma\left(T_s\right)^4 + \left(1-\varepsilon\right)W_{background}\right] + W_{atm}$$

where

- $\tau$ : atmospheric transmissivity.
- $\varepsilon$ : emissivity of the object's surface.
- $\sigma$ : Stefan–Boltzmann constant ($5.67 \times 10^{-8}$ $Wm^{-2}$ $K^{-4}$).
- $T_s$ : surface temperature of the object (K).
- $W_{background}$ : background radiation from surrounding surfaces.
- $W_{atm}$ : infrared radiation emitted by the atmosphere.

Modern thermographic software incorporates these corrections by default, enabling more accurate temperature measurements. Users must input values for surface emissivity, relative humidity, air temperature, distance to the object, and background temperature (**Figure 24**). The latter can be estimated by measuring the temperature of a crumpled aluminum foil piece placed between the camera and the object, assuming maximum emissivity (ε = 1.00) (**Figure 25**).

A noteworthy example is the main entrance of the western facade of the Monastery of San Lorenzo de El Escorial, whose fracturing has been meticulously studied [18]. Thermography proved highly useful in investigating whether this fracture, which has a structural explanation, could pose durability issues. To this end, terrestrial thermography was initially employed. However, despite conducting the thermographic inspection, the significant height of the lintel (over 6.00 m) prevented obtaining conclusive results due to the limited viewing angle.

For this reason, aerial thermography was employed: a drone was deployed to capture the corresponding thermogram, which clearly demonstrated the homogeneity of the lintel's constituent material and, consequently, the absence of durability-related damage associated with the existing fractures. The difference between the images obtained through aerial and terrestrial thermography is significant (**Figures 26** and **27**).

Another compelling example is the Tower of Hercules, previously mentioned in the context of terrestrial thermography (**Figures 13** and **14**). Given its height of 55 m [19], terrestrial thermography is evidently limited. Therefore, a drone was deployed to conduct the necessary reconnaissance operations and capture the required thermograms (**Figure 28**). The drone facilitated a detailed analysis of the neoclassical lantern atop the tower, where the most thermally significant points were identified

**Figure 24.**
*Ground-level photograph of the lintel above the main entrance of the Monastery of El Escorial (photo by the author).*

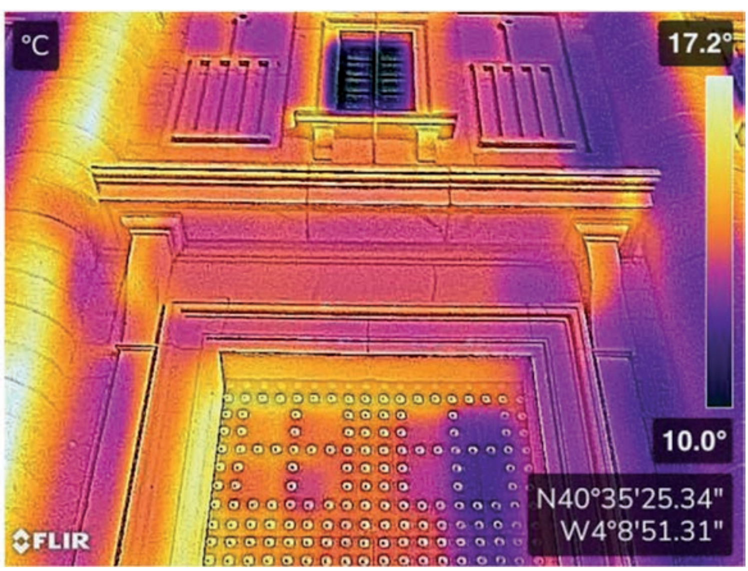


**Figure 25.**
*Terrestrial thermogram corresponding to* **Figure 24***, showing the different materials used (photo by the author).*

(**Figures 29** and **30**). Additionally, a comprehensive examination of the facade was performed, with the drone positioned at various points to capture images from appropriate heights (**Figures 31–33**). The thermographic analysis confirmed the absence of significant anomalies, although minor irregularities were observed in some stone blocks, attributable to weathering effects on the granite (**Figure 32**). These irregularities are negligible and pose no durability concerns.

**Figure 26.**
*Drone hovering in front of the lintel of the main entrance of the Monastery of El Escorial (photo by the author).*

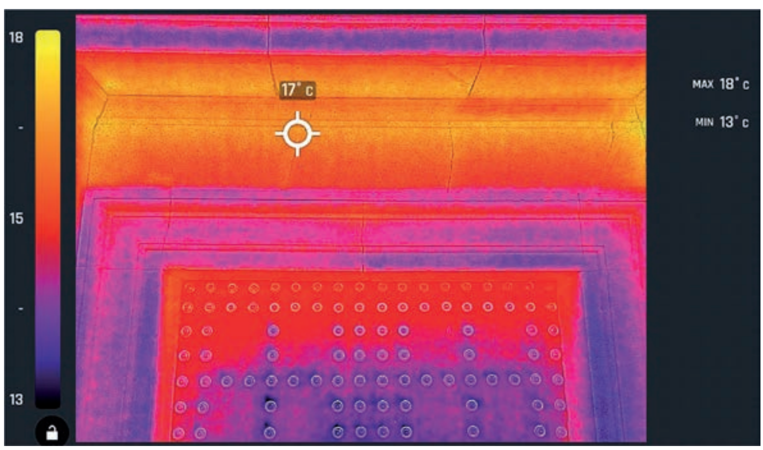


**Figure 27.**
*Aerial thermogram, captured with a drone, of the lintel above the main entrance of the Monastery of El Escorial (photo by the author).*

## 7. Conclusions

Thermography, as demonstrated in this study, is a powerful, non-invasive technique for the assessment and preservation of architectural heritage. The application of both terrestrial and aerial thermography has proven effective in identifying thermal anomalies associated with structural pathologies such as moisture infiltration, material heterogeneity, and hidden structural elements. The case studies presented, including the Tower of Hercules, La Giralda, and the Cathedral of León, highlight the method's capacity to provide detailed diagnostic information without physical contact.

Aerial thermography, facilitated by drone-mounted cameras, enables the inspection of hard-to-reach areas, offering new perspectives for heritage diagnostics. The technology's ability to detect thermal differences between materials of distinct compositions supports its usefulness in evaluating the state of historical facades and internal structures.

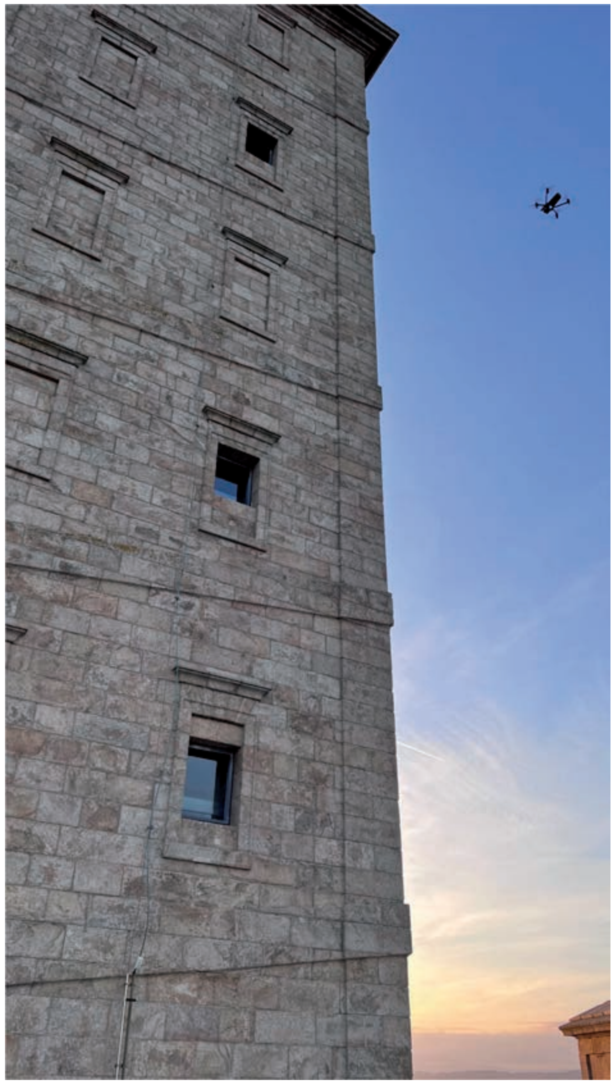

**Figure 28.**
*Drone flying alongside the Tower of Hercules to capture photographs and thermograms (photo by the author).*

Furthermore, the findings underscore the importance of selecting appropriate environmental conditions, such as measuring during twilight hours, to enhance thermal contrast and measurement accuracy. The research also confirms that material properties, including emissivity, transmissivity, and reflectivity, significantly influence the quality of thermographic data.

Thermography is a powerful, non-contact technique for obtaining temperature data from objects. Its applications are vast, given that all materials emit infrared radiation. Aerial thermographic inspection complements conventional heritage assessment by offering novel perspectives and the ability to access hard-to-reach areas.

This technology significantly enhances the speed and thoroughness of inspections, particularly when surveying large surfaces. Drone-based thermography reduces labor costs and ensures comprehensive coverage, minimizing the risk of overlooking critical areas.

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**Figure 29.**
*Junction between the original Roman section and the lantern added in the eighteenth century, highlighting the area with the highest recorded temperature (photo by the author).*

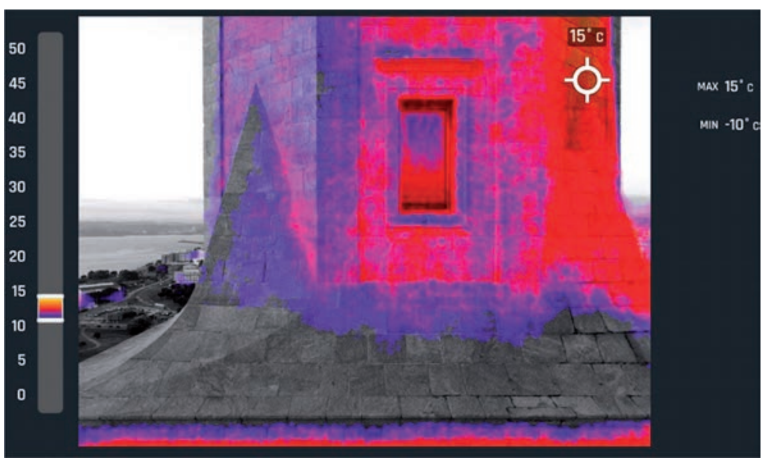


**Figure 30.**
*Thermogram analyzing the lantern atop the tower, marking the point of maximum temperature (photo by the author).*

As a non-destructive diagnostic tool, thermography, when combined with *in-situ* observations, provides valuable insights into the thermal behavior of heritage structures. It facilitates the detection of patterns, anomalies, and potential structural pathologies within the building envelope.

The conducted surveys confirm the utility of aerial thermography for heritage applications. By capturing thermal data remotely, it is possible to assess the condition of historical elements without direct contact, preserving the integrity of the site. The technique's non-invasive nature and compatibility with other diagnostic methods underscore its potential as a standard practice in heritage conservation.

The information obtained through thermographic analysis aids in predicting future thermal anomalies, supporting preventive conservation strategies. Consequently, aerial thermography serves as a valuable tool for heritage professionals, providing insights that contribute to the ongoing preservation of historical structures.


**Figure 31.**
*Thermogram captured by the drone to analyze the window of the first-level chamber on the northern facade, indicating the point of minimum temperature (photo by the author).*

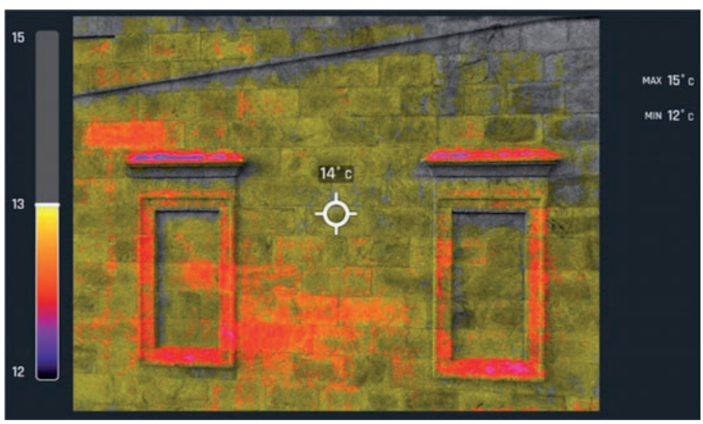


**Figure 32.**
*Thermogram captured by the drone analyzing the opaque windows of the top level on the northern facade (photo by the author).*

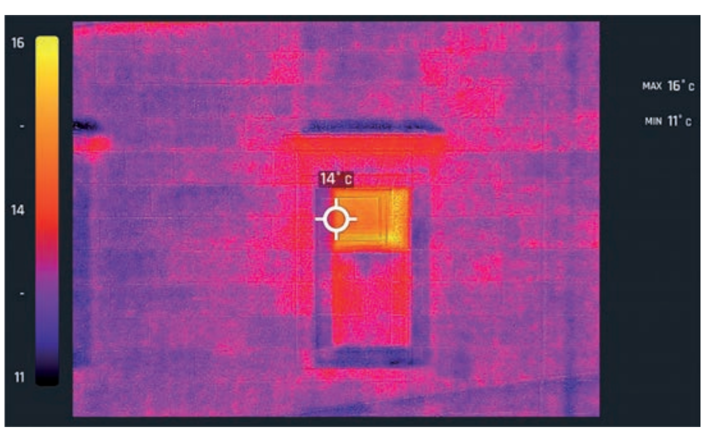


**Figure 33.**
*Thermogram captured by the drone examining the highest window on the northern facade (photo by the author).*

In conclusion, infrared thermography stands as a valuable tool for heritage conservation. Its integration into regular inspection protocols can contribute to the early detection of deterioration patterns, thereby supporting preventive conservation strategies and ensuring the long-term preservation of historical structures.

The experiences documented in this study are transferable to similar projects, demonstrating the versatility of drone-mounted thermal cameras in heritage contexts. As these technologies continue to evolve, their role in architectural diagnostics and cultural heritage conservation is expected to grow, offering innovative solutions for safeguarding our historical legacy.

## Conflict of interest

The author declare no conflict of interest.

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