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Thermography Applied to Damage Diagnosis over Monuments and Ancient Constructions

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ABSTRACT
Thermography is a technique based on the detection of radiation emitted by bodies, converting the information obtained in images into information on the temperature of their surface. The reduction in cost of these cameras and their incorporation into drones, as an additional element, opens the doors to a very useful new microtechnology, which we can take advantage of to auscultate monuments and their constituent materials.

Introduction

Normal cameras detect visible light emitted by objects; Normal cameras are capable of capturing this visible light in a photograph. Instead, thermal imaging cameras do the same with infrared emissions. Infrared rays have a lower frequency than visible light. For this reason, the human eye cannot detect them. However, infrared rays can be organoleptically perceived as heat. The human eye is not sensitive to infrared radiation emitted by an object, although our skin is. So, thermal imager records temperature of objects in an image.

Depending on the model of thermal imager, it can be sensitive to hundredths of a degree.

Thermography is an instrumental diagnostic and auscultation technique for heritage materials of great interest [1-3]. Thermography allows you to accurately measure the surface temperatures of an object without maintaining physical contact with it.

The main characteristics of thermography are:

- It is not invasive. This works remotely.
- Collects the observed element in an image, allowing the analysis of the temperature.
- Allows quick viewing of stationary objects.
- The images provide us with information on the temperature, thermal patterns, behaviors and existing anomalies.

Thermographic images are used to search for so-called "hot" points, those points of an element whose temperature is higher and, therefore, stand out in the thermal image or thermogram. Thus, the author of this article has used thermography, for example, to locate underground structural metal elements (Figure 1) or underground installation pipes (Figure 2), to give just a few examples. Infrared thermography is essential for a good analysis of the state of the building envelope to locate possible thermal bridges, insulation defects, humidity and many other pathologies of buildings [4]. Hence its interest for its use in the field of heritage inspection

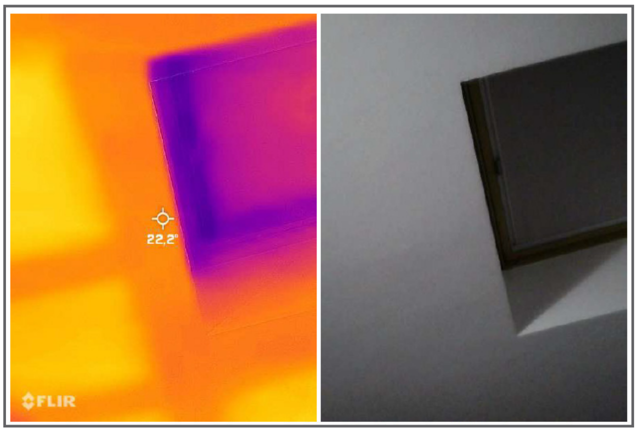

Figure 1: Thermographic analysis of a house under its roof, for the location of hidden beams and structural elements and heat losses in the skylight. We can see, on the left, the photograph taken by a thermographic camera and, on the right, the same photograph taken by a photographic camera. (photographs by the author).

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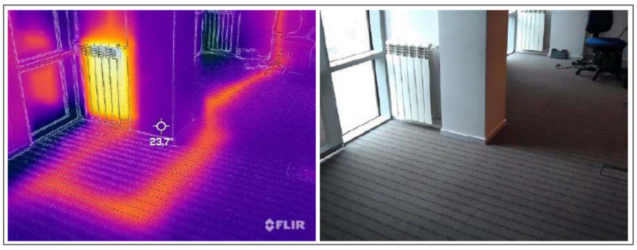

Figure 2: Location of heat conduction for the supply of a radiator, when it was turned on and emitting heat, in an office building. We can see, on the left, the photograph taken by a thermographic camera and, on the right, the same photograph taken by a photographic camera. (photographs by the author).

In recent years, many models of thermal imaging cameras have appeared. These cameras are increasingly compact and increasingly accessible, thanks to their cheapness. Cameras today are much cheaper and this allows many technicians to use them. Similarly, this reduction in cost is allowing the use of this technology not to be extraordinary. Thus, we have been able to use thermal imaging cameras in many applications in recent years and we have been able to attach thermal imaging cameras to many devices in recent years.

Thermography Fundamentals

As we saw in the Introduction, thermography is a technique that is based on the detection of radiation emitted by bodies, converting the information obtained in images into information about the temperature of their surface.

Any object with a temperature above absolute zero (0 Kelvin = -273.15°C) emits infrared radiation (IR radiation). The human eye cannot see this radiation as it is blind to this wavelength (Figure 3). The thermal imaging camera is not blind to these wavelengths. The heart of the camera, the infrared detector, is sensitive to infrared radiation. Due to the intensity of the infrared radiation, it determines the temperature of the object's surface and makes it visible to the human eye using a thermal image. This process is called thermography.

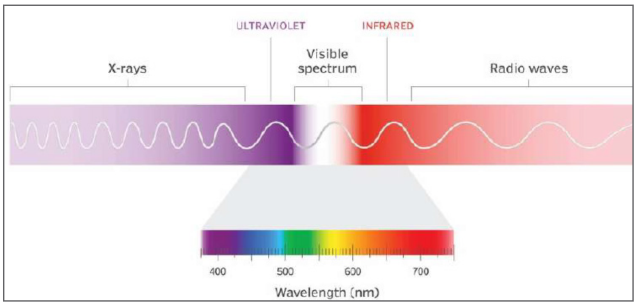

Figure 3: Visible and invisible light [5].

To make infrared radiation visible, the detector detects it, converts it into an electrical signal, and assigns each signal a certain color that appears on the screen of the thermal imager. What a thermal imaging camera does could be defined as the translation of wavelengths of the infrared spectrum into wavelengths visible to the human eye (colors).

Contrary to what many people think, a thermal imaging camera does not allow you to see inside objects; a thermal imaging camera makes visible the surface temperature of objects. However, when there is an internal object that transmits an extreme temperature, this object becomes visible to a thermal imager (Figure 1 and Figure 2).

The radiation recorded by a thermal imaging camera is made up of the emitted, reflected and transmitted radiation coming from the objects present in the field of view of the camera (Figure 4) [6].

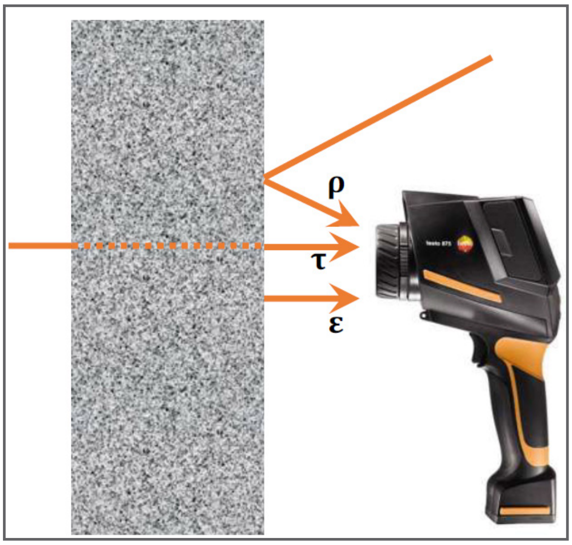

Figure 4: Radiation emitted (ε), reflected (ρ) and transmission (τ) from an object, recorded by a thermographic camera (diagram prepared by the author).

- Transmission (τ). Transmission is the ability of a material to let infrared radiation pass, that is, to transmit it. A thin sheet of plastic, for example, has a high transmissivity. Therefore, if we try to measure the temperature of a thin plastic sheet placed in front of the façade of a house using a thermographic camera, the result of the measurement will not be the temperature of the sheet, but that of the façade of the house. Most materials do not allow infrared radiation to pass, so the transmissivity of most materials is practically 0 and can be neglected.
- Emission (ε). Emission is the ability of a material to emit infrared radiation. This capacity is expressed as a percentage. This depends on the material itself and the properties of its surface. For example, the sun has an emissivity of 100%. This value never appears in everyday work. A material with a very high emissivity value is, for example, concrete, with 93%. This means that 93% of the infrared radiation comes from the concrete itself.
- Reflection (ρ). The remaining 7% are reflections from the surroundings of the material / object to be measured, ie the temperature reflected from the object. In a thermographic camera, both the emissivity data and the reflected temperature data can be entered, in order to obtain the most accurate thermal image possible.

Thermal imaging cameras generate an image in which each pixel contains the temperature value. These images are coded in color levels (pseudocolor), where cooler colors (blue) typically represent lower temperatures and warmer colors (red) represent higher temperatures.

Aerial Thermography

As a complement to what we have exposed in the previous section, in recent years thermographic cameras have been incorporated into drones. This is what we know as aerial thermography: to the experience gained inspecting buildings with drones we now add thermography [7,8]. Thus, we can see in Figure 5 a quadcopter drone approaching a medieval bridge for inspection. In this case, it is the Grajal Bridge, visually inspected by the author [8,9].

Figure 5: Drone equipped with a thermal imaging camera, approaching a medieval bridge (Puente del Grajal) for inspection (photograph by the autor).

Next, we can see the thermographic analysis of the interior of a vault of a masonry arch bridge (Figure 6) and of the gable end of the bridge abutment with the range of temperatures (Figure 7).

Figure 6: Comparison between the real image (left) and the image captured by the thermographic camera (right), inside the vault of the Puente del Grajal. We can see, on the right, the photograph taken by a thermographic camera and, on the left, the same photograph taken by a photographic camera. (photographs by the author).

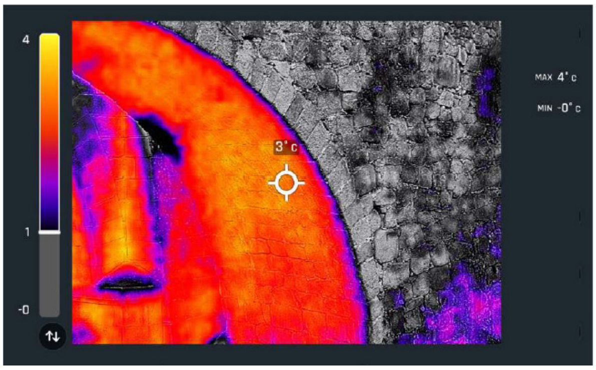

Figure 7: Thermographic analysis of the Grajal Bridge, in Spain, with relative scale of temperatures recorded during the inspection (photo by author).

One reason to use aerial thermography is the fact that it is recommended to detect a thermal anomaly with a viewing angle of 70° to almost 90° in relation to the analyzed surface. A manual camera can hardly fulfill this condition; a drone with a thermal camera easily meets this condition.

A limiting factor during the measurement of values can only be hydrometeorological conditions that can significantly influence the measurement accuracy. During the measurement, an ambient temperature of 25°C with a sun intensity of 1,000 Wm-2 and some clouds is ideal. In this case, the contrast is high enough to reflect all the flaws.

Objects with a temperature higher than absolute 0 (0ºK or 273ºC) emit electromagnetic energy in the infrared range (0.75 µm - 100 µm). According to the Stefan-Boltzmann law the emitted infrared radiation increases with the temperature of the bodies [10].

The Stefan-Boltzmann law is applicable to black bodies, which are perfect emitters of infrared radiation, or what is the same, have an emissivity (ε) equal to 1 [11,12]. The emissivity is the capacity that has whole body to radiate energy. Real bodies have ε < 1. For this reason, in addition to emitting infrared radiation, they also reflect a part of the incident infrared radiation.

Therefore, the total infrared radiation that is detected by a thermal imager is the sum of the emitted radiation ($\varepsilon_\sigma (T_s)^4$) and the reflected radiation ($(1 - \varepsilon)_{Wbackground}$) by the observed object, considering that the absorption of infrared radiation by the air mass existing between the studied object and the camera sensor is not significant (when the existing distance is a few meters or the infrared sensor works in the range of 3-5 or 7-14 µm, where the transitivity of the atmosphere to infrared is maximum).

In the event that the distance between the camera and the studied object is greater (as occurs in aerial observations), it is necessary to introduce another factor: atmospheric emission (W_{atm}), as well as the transmissivity of the atmosphere to radiation.

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

Thermographic cameras allow us to measure, in real time, the radiant energy emitted by objects and determine their surface temperature from a distance.

Today, most thermal imaging camera software already includes this type of correction. This allows the development of more accurate measurements of the temperature of the observed objects. Despite this, it is necessary to enter the values of emissivity, relative humidity and air temperature, the distance to the object and the temperature reflected by the surrounding environment. This last parameter can be estimated by measuring the temperature reflected by an irregular piece of aluminum foil, placed between the camera and the object to be measured, and using the maximum emissivity value (ε = 1).

Thermographic cameras allow us to measure, in real time, the radiant energy emitted by objects and determine their surface temperature from a distance.

Inspection of Monuments by Thermography

In recent years, the new thermographic cameras have dropped a lot in price and can be used to appreciate holes and anomalies. The campaigns must be carried out at dusk or dawn, because what the cameras detect is the different temperature that is manifested in the walls of the monument [13]. It is in those moments when it is easier to observe the eventual presence of non-homogeneous zones that will dissipate heat in a different way. This makes it possible to locate constructive defects in constituent materials [14-18].

We have used thermography to pinpoint areas of moisture in walls, often with little effective result. To do this, we base ourselves on the fact that humid areas must be cooler due to evaporative heat loss, but the thermal history often masks useful signals. We have an example in Figure 9, where we analyze La Giralda, the bell tower of the Seville Cathedral [19]. The image captured with a thermographic camera shows the area of humidity, clearly visible to the human eye, as we see in the photograph on the left.

We have also used thermography to detect blistering in paints and plasters, as well as other surface or structural characteristics capable of producing thermal contrasts. Next, we have a series of images captured with a very simple thermographic camera, a FLIR One model. It is an 80 x 60 thermal resolution camera, with an object temperature range of -20ºC to 120ºC and an operating temperature of from 0ºC to 35ºC. Its accuracy is ±3°C or ±5%, typical percentage of the difference between ambient and scene temperaturas.

With it, we have analyzed the Giralda, the bell tower of the Seville Cathedral (Figure 8 and Figure 9), the Torre del Oro in Seville too (Figure 10), the bell tower of the Oviedo Cathedral (Figure 11), the Roman lighthouse Tower of Hercules in La Coruña (Figure 12 and Figure 13), fragments of the Monastery of El Escorial (Figure 14) or the Palma de Mallorca Cathedral (Figure 15 and Figure 16), to give just a few examples. The images collected below illustrate the usefulness of thermography for this purpose.

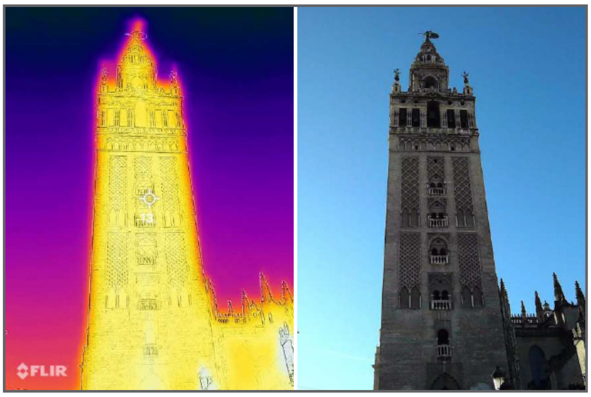

Figure 8: hermographic analysis of the north façade of the Giralda bell tower. We can see, on the left, the photograph taken by a thermographic camera and, on the right, the same photograph taken by a photographic camera. We can see, on the left, the photograph taken by a thermographic camera and, on the right, the same photograph taken by a photographic camera (photographs by the author).

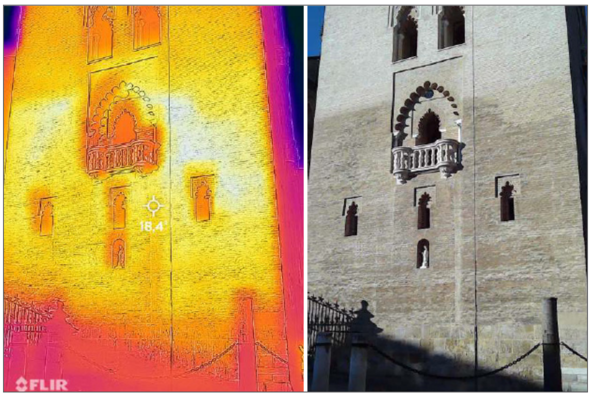

Figure 9: Thermographic analysis of the lower east façade of the Giralda bell tower, bell tower of the Cathedral of Seville, where humidity is observed. We can see, on the left, the photograph taken by a thermographic camera and, on the right, the same photograph taken by a photographic camera. (photographs by the author).

Figure 10: Thermographic analysis of the southern flank of the façade of the Torre del Oro, in Seville. We can see, on the left, the photograph taken by a thermographic camera and, on the right, the same photograph taken by a photographic camera (photographs by the author).

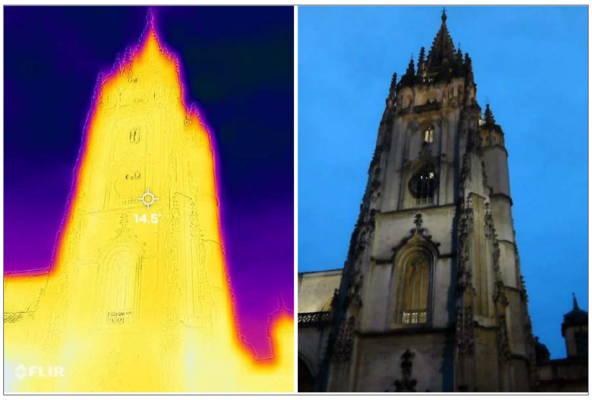

Figure 11: Thermographic analysis of the west façade of the bell tower of the Oviedo Cathedral. We can see, on the left, the photograph taken by a thermographic camera and, on the right, the same photograph taken by a photographic camera (photographs by the author).

Figure 12: Thermographic analysis of the Roman lighthouse Torre de Hércules, in La Coruña. We can see, on the left, the photograph taken by a thermographic camera and, on the right, the same photograph taken by a photographic camera (photographs by the author).

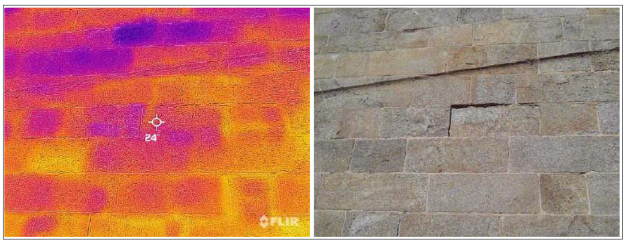

Figure 13: Detailed thermographic analysis of the constituent materials (granite with mortar) of a fragment of the façade of the Torre de Hércules Roman lighthouse. We can see, on the left, the photograph taken by a thermographic camera and, on the right, the same photograph taken by a photographic camera (photographs by the author).

Figure 14: Thermographic analysis of the northwest tower of the Monastery of El Escorial, from the west façade (photographs by the author).

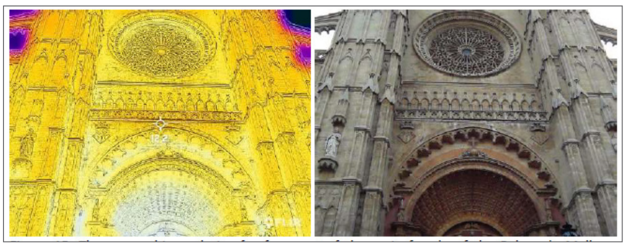

Figure 15: Thermographic analysis of a fragment of the main façade of the Palma de Mallorca Cathedral (photographs by the author).

Figure 16: Exterior thermographic analysis of the chevet of the Palma de Mallorca Cathedral (photographs by the author).

Conclusions

Thermography is a procedure that we can use to obtain information about the temperature of an object at a distance, without physical contact with the object.

The applications of infrared thermography are almost endless, since all bodies emit heat. Aerial thermographic inspection is nothing more than an aid for heritage experts, which allows obtaining a new and very relevant point of view due to the angle and distance from which they are taken.

We can also gain inspection speed when it comes to large surfaces to inspect. The help of the drone can mean significant cost savings in working hours and the guarantee of not leaving any area unchecked.

Thermography is a non-destructive technique that, complemented with other field information obtained in situ, allows us to obtain real data on its state and the existence of possible pathologies of the building's construction elements. With this, we can obtain information on patterns, behaviors and thermal anomalies in certain areas of the surrounding of the monument or of the old construction, for an adequate pathological diagnosis or, in the best of cases, to verify the good condition of the old construction.

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