



Review

Infrared Thermography's Application to Infrastructure Inspections

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Received: 20 July 2018; Accepted: 10 September 2018; Published: 12 September 2018



Abstract: Health monitoring and prediction in different types of structures is essential in order to maintain optimal conditions. Some of the pathologies that affect their structural stability are characterized by distinct thermal properties compared to unaltered areas. Infrared thermography (IRT) is a technique based on the acquisition of the thermal radiation of the bodies using thermal sensors of infrared (IR) cameras, which produce an image of the thermal infrared radiation captured through the conversion of the radiation values to temperature values. Therefore, this technique can be used in different studies to analyse structures with one or more pathologies based on their anomalous thermal behaviour with regard to the unaltered surroundings. As a consequence, this review presents various IRT applications to infrastructure inspections, showing the utility of the technique.

Keywords: infrared thermography; structural pathologies; infrastructure inspections

1. Introduction

Taking the necessary measures to preserve and maintain an infrastructure during its lifetime at different stages is a global concern that affects social and economic development in all countries [1]. For this purpose, it is fundamental to use the best methods of inspection, with continuous updates and improvements [2].

Nowadays, in the infrastructure field, Non-Destructive Testing (NDT) methods are among the most widely used and have increased in popularity in recent decades. The main reason is that most NDT methods work remotely, i.e., without contact. The lack of contact allows for analysis of the performance even for structures that are difficult to access or under insecure conditions, such as structures that are at very high or low temperatures, or are unsteady. Other great advantages are that NDT methods do not damage the infrastructure under study, and avoid the lack of objectiveness and slowness of the traditional methods. Regarding those NTD methods that require contact with the analysed surface, they usually compensate for this disadvantage by adding information on the non-visible areas of the structure under study [1].

Therefore, it is possible to geometrically characterize a structure and even its individual materials with NDT techniques, including the detection and characterization of surface and even subsurface pathologies. Regarding thermal pathologies, they cause an abnormal temperature distribution with respect to the distribution of the rest of the structure [3]. Examples of thermal pathologies are thermal bridges and air infiltration in buildings, cracks in pavements and bridges, and moisture. Moreover, the thermal characterization of materials is also important for different uses, for example in a building envelope, to quantify the real energy demand in the structure.

Within the context of thermal analysis in structures, the Infrared Thermography (IRT) technique is the optimal NDT method. The reason for this is that it measures the temperature of any surface, including the effect of subsuperficial phenomena in some cases, through the translation of the radiation emitted by the body under study within the thermal infrared band to temperature values. The measurement of radiation is achieved by the thermal sensor of an infrared (IR) camera [4], presenting a large number of applications ranging from medical imaging [5] to infrastructure inspections [6]. It is important to note that, depending on the performance required, IRT can be combined with other NDT methods, as this would increase confidence, deepen the analysis and make the validation of the particular study results more robust [2]. For example, Solla et al. [7] and Sfarra et al. [8] combine the Ground Penetrating Radar (GPR) and optical and ultrasonic techniques with IRT, respectively.

Thus, in this paper, some IRT applications to infrastructure inspections are reviewed, showing the utility of the technique and classifying the works according to the type of infrastructure analysed: buildings, civil infrastructure or heritage sites. However, prior to that review, Sections 2 and 3 describe the theory and the different approaches of this NDT method, and Sections 4 and 5 describe its advantages and restrictions, as well as the latest thermal data processing techniques applied to infrastructure inspections.

2. Theory of Infrared Thermography

The conversion from radiation values measured by the thermal sensor of an IR camera to accurate absolute temperature values is performed if the following parameters are known: atmospheric temperature and relative humidity (T_{atm} and RH_{atm}), distance between the IR camera and the object under study (d), emissivity of the object surface (ϵ), and transmissivity and reflected temperature of the surroundings (T and T_{refl}).

The radiation measured can be defined as a collection of discrete particles called “photons” or “quanta,” where each particle has an energy given by the Planck-Einstein equation [9,10]:

$$e = h \times \nu = (h \times c) / \Lambda, \tag{1}$$

where e is the photon energy (J), $h = 6.626 \times 10^{-34}$ (J·s) is Planck’s constant, ν is the photon frequency (1/s), c is the speed of light in vacuum (m/s) and Λ is the photon wavelength (m). The frequency and wavelength values of a photon are within the values of the electromagnetic spectrum, which is divided into a number of wavelength intervals, called spectral bands, as shown in Figure 1 [11]:

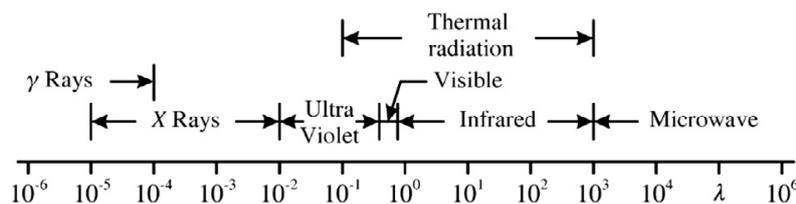


Figure 1. Electromagnetic spectrum (Λ in micrometers (μm)).

Among the spectral bands, the range 0.4–1000 μm belongs to the infrared band, which is divided into four bands: near infrared (NIR, 0.4–1 μm), short-wave infrared (SWIR, 1–3 μm), mid-wavelength infrared (MWIR, 3–5 μm) and thermal infrared (TIR, 7–14 μm). In the 5–7 μm range, infrared radiation is not transmitted through the atmosphere, in such a way that this range is called the atmospheric window. Moreover, the Infrared Thermography technique only measures the radiation emitted in the TIR band (thermal radiation) [12]. The other spectral bands of the infrared are used to analyse the water stress of vegetation (NIR and SWIR bands), to study the soil water content (SWIR band), to analyse geological features (SWIR band) [13–15] or to visualize the vapour and gas molecules to detect gas leaks (MWIR band) [16,17], among others.

On the other hand, the thermal radiation emitted by a body depends on its thermal state, i.e., is related to its temperature value. The temperature comes from the thermal radiation received and from the internal phenomena that occur in an object, moving its atoms and molecules with a higher or lower vibration depending on its temperature value. Then, the mean velocity of the atoms and the molecules is a measure of the temperature of a body.

In order to express mathematically the thermal radiation emitted by an object, the Stefan-Boltzmann law is used [18]:

$$E_b = \sigma \times T_b^4, \tag{2}$$

where E_b is the total thermal radiation emitted by a black body per unit area (W/m^2), σ is the Stefan-Boltzmann's constant equal to 5.67×10^{-8} ($W/(m^2 \cdot K^4)$) and T_b is the absolute surface temperature of the black body (K). A black body is defined as an ideal body, which emits all the thermal radiation received according to its thermal state/temperature value. Nevertheless, ideal bodies do not exist and, as a result, for the purpose of analysing the ideal response of an object subjected to certain radiation, "black body simulators" are manufactured [19]. With this, it is deduced that real bodies will never be able to emit all the thermal radiation received as a relationship to their temperatures. Therefore, emissivity (ϵ) is defined as a parameter that indicates the ratio between the thermal radiation emitted by a real body ("grey body") and that of a black body at the same temperature [20]. Then, the adaptation of the Stefan-Boltzmann law to real bodies implies the introduction of an emissivity parameter as in Equation (2):

$$E_g = \epsilon \times \sigma \times T_g^4, \tag{3}$$

where the emissivity value ranges from 0.1 to 0.99 [12], and E_g and T_g are the thermal radiation emitted by a grey body and its temperature, respectively.

Therefore, the remaining thermal radiation received by the thermal sensor of an IR camera, which was not emitted by a grey body due to its thermal state and, thus, that does not affect its temperature value, comes from two different sources: reflected and transmitted thermal radiations. The first term is referred to the fraction of the thermal radiation received by the grey body but redirected after hitting its surface; and transmitted thermal radiation is the fraction that passes through the grey body without any alteration in the temperature of the object.

Then, the radiation measured in IRT applications is the sum of the thermal radiation emitted by the body under study that is linked to its temperature value, plus the thermal radiation reflected from the emission of the thermal radiation of the surroundings. Given that IRT studies are usually performed on opaque materials, the transmitted thermal radiation can be considered negligible. In addition, during the measurement, the atmospheric attenuation on the reflected and emitted thermal radiations to the IR camera occurs [21]. Therefore, the equation of the total thermal radiance measured by the IR camera (W_{tot} (W/m^2)) is as follows:

$$W_{tot} = \epsilon \times T \times W_{obj} + (1 - \epsilon) \times T \times W_{refl} + (1 - T) \times W_{atm}, \tag{4}$$

where ϵ is the emissivity value of the object, T is the atmospheric transmittance; and W_{obj} (W/m^2), W_{refl} (W/m^2) and W_{atm} (W/m^2) are the thermal radiation emitted and reflected from the body, and the thermal radiation absorbed by the atmosphere, respectively.

It is important to note that W_{obj} is referred to the thermal radiation emitted by the body, acting as a black body at the same temperature; W_{refl} , in addition to depend on the thermal radiance emitted by the surrounding to the body, also depends on the reflective properties of the body surface. For this reason, W_{refl} is not equal to W_{obj} , and the adjustment is performed through the determination of the reflected temperature (T_{refl} (K)). Moreover, T depends on T_{atm} (K), RH_{atm} and d (m) [22]. Therefore, knowing previous parameters (T_{refl} , T , T_{atm} , RH_{atm} and d), ϵ is the factor remaining in order to use Equation (3) and obtain the real temperature value of the object during the IRT inspection, since $W_{obj} \times \epsilon$ is equal to E_g .

If the emissivity value is not calculated during the use of the IR camera, the temperature value measured is known as “apparent temperature.” In qualitative approaches and using the same material, or materials with similar emissivity values, IRT studies can use “apparent temperatures” [23]. Otherwise, there are several tables with emissivity values of different materials at different temperature values and according to their superficial state (polished, grainy, oxidized) [24]. Nevertheless, in-situ emissivity tests are always recommended when a high accuracy of the measured temperature values is required [25], for instance in quantitative approaches

For the case of T_{refl} , a rubbed aluminium foil is placed parallel to the object surface under study, and the measurement is performed establishing 1 as the emissivity value for the measurement in the settings of the IR camera, as described in the standard [26]. With this, given that aluminium has low emissivity, the temperature value measured is the reflected temperature linked to the objects in the environment of the object under study [22]. As a consequence, the thermal radiation measured from the surroundings and the reflective properties of the body can be calculated using Equation (2), obtaining W_{refl} . However, in practical cases, the recommendation is that the lens of the IR camera are not focused on the object with perpendicular direction in order to avoid the measurement of the self-reflection of the lens on the surface under study [27].

Concerning the atmospheric attenuation of the thermal radiation measured by the thermal sensor of an IR camera, an “attenuation coefficient” introduces both the atmospheric transmittance (T) and thermal radiation absorbed by the atmosphere (W_{atm}). Generally, this parameter is calculated using two different approaches: (i) direct: the operator calculates the “attenuation coefficient” from the atmospheric temperature and relative humidity; (ii) indirect: introducing T_{atm} , RH_{atm} and d values in the IR camera [28].

3. IRT Approaches

Depending on the type of IRT test to be performed, there are four different combinations regarding the presence or absence of an external and artificial mechanism of thermal excitation and the purpose of the investigation.

First, referring to the presence or absence of an external and artificial mechanism of thermal excitation in the object under study, active and passive approaches are possible. In the case that there is a natural thermal excitation source, such as solar radiation [29], the approach is known as “passive IRT.” With passive IRT, the natural thermal behaviour of the body is measured, since the analysis is performed under real conditions without any artificial heat source. Otherwise, the IRT analysis can be conducted using artificial heat sources, in order to measure the heating or cooling processes of the object under study, during or after the thermal excitation. This approach is called “active IRT,” and the different thermal stimulations can be classified as follows:

- Traditional thermal excitation techniques: thermal blankets and heat guns. Although they are still in use today, new thermal excitation techniques have been developed to improve the defect detection rate [30].
- New thermal excitation techniques: optical stimulation techniques. They can emit both pulses of energy and continuous and modulated heat to the structure under study using flash and halogen lamps, respectively. However, these new techniques do not provide enough thermal contrast in some specific material defects, such some inserts in carbon-fiber-reinforced polymers (CFRPs). Therefore, advanced thermal excitation techniques have been used to overcome the limitations of optical stimulation techniques [30].
- Advanced thermal excitation techniques: there are several advanced methods, such as vibrothermography, thermoinduction thermography, laser spot thermography and ultrasound-excited thermography. In vibrothermography, thermal stimulation is induced by the effect of mechanical excitation applied externally to the material, identifying with an IR camera the possible defects through the heat generated by friction. On the other hand, in thermoinduction thermography, thermal excitation is the circulation of a current at certain frequencies along

an induction coil, generating eddy currents within the material to be inspected. Because the density of the eddy currents is different in defects, the heat produced by the Joule effect will be different in areas with defects and can be identified with an IR camera. Regarding laser spot thermography, it is a novel method for surface crack testing and imaging, with the advantages of being deployable remotely, adjusting the focus position explicitly, and being suitable for the detection of surface crack as the heat flow propagates mainly near the surface [31]. Finally, ultrasound-excited thermography is one of the variants of vibrothermography, being a contact method in this case. The thermal excitation consists of a sonotrode that is in physical contact with the test piece to excite the material with ultrasonic excitation, generating three-dimensional vibrations that travel through the material and consequently generating heat that is measured by an IR camera [32].

Moreover, active IRT presents the following sub-classifications:

- Depending on the relative positions between the object, the heat source and the IR camera: Reflection and Transmission modes. In the Reflection mode, the heat source and the IR camera are on the same side with regard to the specimen under study, being more important to measure the fraction of radiation reflected than the fraction of radiation transmitted by the object. Otherwise, if the body is located between the heat source and the IR camera, the method corresponds to the transmission mode, where the measurement of the thermal response of the body is the main objective.
- Depending on the type of heating process: Pulsed Thermography (PT) and Lock-in Thermography (LT) [33]. PT consists of thermal stimulation of the object under study in short pulses, with duration of ms [34]. However, in LT, the heat flux applied is modulated at a given frequency [35].

On the other hand, regarding the purpose of the investigation, the thermographic technique can be applied qualitatively or quantitatively. In cases where precise knowledge of the temperature values in the thermal images is not required, and the aim is to focus on the temperature distribution or the relative pixel values, “qualitative IRT” is applied. It is used for all IRT applications in which the main objective is to detect the existence or absence of thermal pathologies, without taking into account the classification of the severity of the possible anomalies and the thermal characterization of the materials under study. For instance, for a first rapid IRT inspection of infrastructures that were affected by a recent earthquake, qualitative approach is recommended.

On the contrary, if the aim is at obtaining accurate absolute temperature values, the corrections of the emissivity and the reflected temperature acquired by the IR camera are required, in addition to the compensation of the atmospheric attenuation. If this is the case, the approach is “quantitative IRT.” This approach is used after the detection of possible thermal pathologies in the material under study, identified by means of a qualitative IRT or another different tool, in order to classify the severity and/or to compute some thermophysical properties of the anomalies detected, such as the determination of the depth of detected cracks in a bridge or the water content in the pores of a historic building. In addition, IRT also uses a quantitative approach to calculate various thermophysical parameters of the material under study in order to compute, for example, the overall heat transfer through a building envelope.

4. Advantages and Limitations of IRT Applications to Infrastructure Inspections

After describing the theory and the different approaches of IRT, the main advantages and disadvantages of this technique to infrastructure inspections are represented in the following points:

Advantages

- IRT reduces maintenance and replacement costs on any infrastructure, including the reduction of the cost of energy demand on buildings, provided that thermal pathologies are identified in time before they lead to failures of the structures.

- IRT is a NDT method, in other words, the IR camera used for measurements is not in contact with the infrastructure under study. In this way, the operator can always perform inspections safely.
- IRT is a non-invasive technique. That is, this method not intrude upon or affect the structure in any way.
- IRT provides the results in two-dimensional thermal images, facilitating the comparison between different areas of the infrastructure under study.
- IR camera is practical, affordable and measures in real time, allowing high-speed scanning of the structure (usually up to 30–60 thermal images per second [30]).

Limitations

- Today, IR cameras are still expensive for infrastructure inspections [36].
- The spatial resolution of thermal images is generally low for most infrastructures, especially in large structures. To solve this problem, one possible solution is to develop different thermal data processing techniques applied to thermal images in order to take advantage of all the information contained in the latter [37]. The most recent techniques are described in the following section.
- The accuracy of temperature measurement in standard IR cameras is not as good as in contact methods [4], such as thermocouples, having an accuracy of $\pm 2\%$ or worse [38].
- In most IRT studies, the interpretation of thermal images is performed by the human operator, which implies a high level of subjectivity and mainly relies on the expertise of the operator. To avoid misinterpretation, the automation of thermal images interpretation is performed in recent IRT researches as a solution [37,39,40].

5. Recent Thermal Data Processing Techniques Applied to Infrastructure Inspections

Among the most recent and important thermal data processing techniques applied to infrastructure inspections are the following:

(1) Pulsed Phase Thermography (PPT)

PPT is based on the LT post-acquisition, although the input thermal data has to be acquired in a similar way to PT: capturing a sequence of thermal images during the decay curve of the surface temperature of the structure under study, heating it with short pulses, but at different frequencies and not just at one as in PT [41].

Therefore, instead of analysing the temperature evolution as in the PT post-acquisition, PPT studies the amplitude and phase of the thermal images, as in the LT post-acquisition. To do this, PPT transforms the sequence of thermal images into the frequency domain using the Discrete Fourier Transform (DFT).

(2) Principal Component Analysis (PCA)

PCA is a technique in which its theory and adequate procedures according to the final objective of each study are well known in the thermography field. The objectives of this method is: (i) to reduce the number of variables in a data set to a smaller number and, at the same time, to lose as little information as possible; (ii) to highlight the differences and similarities in the data set.

Therefore, this tool has a lot of applications in active thermography, where it reduces a temporal sequence of thermal images from 3D data (x, y coordinates of the image, adding as third axis the total images of the sequence taken during the test) to different 2D thermal images, where each image describes partially the change of temperature value of each pixel along the time period [37].

(3) Thermographic Signal Reconstruction (TSR)

TSR is a method based on polynomial adjustment of the time history of each pixel from a sequence of thermal images. Therefore, the temperature evolution is adjusted to a polynomial of n degrees. It is highlighted that in this technique a logarithmic conversion of the time history of each pixel

is recommended to improve the thermal propagation difference between a pixel with defect and a defect-free pixel in the polynomial adjustments. In addition, second and third derivatives of the polynomials provide more information about defects [30].

6. IRT Studies in Infrastructure Inspections

The following sub-sections present applications of IRT to infrastructures, classified into three main groups of types of infrastructures: buildings, civil infrastructure and heritage sites. A brief description of each study is presented in each subsection, as well as a summary table covering all the studies.

6.1. Buildings

Both in the past and in recent days, there have always been several IRT studies applied to buildings, where the trend continues to increase. The main reason of this increase is that the building sector is responsible for consuming up to 40% of the total energy in developed countries [39], being a very important sector to be analysed in order to obtain more and more energy efficiency and savings. For this reason, there are IRT studies that range from the thermal characterization of building materials to the detection and thermal characterization of building pathologies.

Regarding thermal characterization of building materials, Danielski & Fröling [42] present a quantitative method using passive IRT to measure the overall heat transfer coefficient (U ($W/(m^2 \cdot K)$)) of building fabrics subjected to a non-steady state heat flow, specifically different thick massive laminated spruce timber walls with different thicknesses. Tejedor et al. [43] also compute U using quantitative IRT for multi-leaf walls, in passive mode but in this case under steady state conditions.

In [42], the method for calculating the U parameter consists of two stages, performed simultaneously while the walls under study are exposed to variable outdoor weather conditions:

- In the first stage, the convective heat transfer coefficient (h_{conv} ($W/(m^2 \cdot K)$)) is calculated on a small segment of the examined building fabric with uniform surface temperature. For that, they use an IR camera and three Heat Flux Meters (HFMs) for the acquisition at different time points of the input parameters needed to calculate the different convection heat flows (Q_{conv} (W/m^2)) (Equation (5)), obtaining h_{conv} by a linear regression of Q_{conv} against the difference between the indoor temperature (T_{in} (K)) and the temperature of the interior surface under study (T_{wall_in} (K)).
- In the second stage, with the h_{conv} result of the first stage, the U -value of a large area of the same building fabric is calculated by a linear regression of the conductive heat flow (Q_{cond} (W/m^2)) against the difference between the indoor (T_{in} (K)) and outdoor (T_{out} (K)) temperatures. To obtain Q_{cond} , Equation (6) is used where the input parameters are measured with an IR camera and various indoor temperature sensors at different time periods.

$$Q_{conv} = Q_{cond} - \varepsilon \times \sigma \times (T_{apparent_in}^4 - T_{apparent_wall_in}^4), \quad (5)$$

$$Q_{cond} = h_{conv} \times (T_{in} - T_{wall_in}) + \varepsilon \times \sigma \times (T_{apparent_in}^4 - T_{apparent_wall_in}^4), \quad (6)$$

where $T_{apparent_in}$ (K) and $T_{apparent_wall_in}$ (K) are the apparent temperatures of the indoor and interior surface, respectively.

Although the regression is not perfectly linear due to the rapid changes in weather conditions, a low confidence interval around the mean U -value is obtained on each wall under study if a minimum number of measurements are made during the second stage. For instance, the uncertainty of the U -value is less than 10% by 10 or more thermal images, and less than 5% with at least 27 thermal images. Moreover, the h_{conv} results depends strongly on the experiment's specific conditions and settings, such as wind velocity, surface texture, surface inclination, temperature and nearby objects. For this reason, the uncertainty of the U -value on the walls in the second stage differs between 3% and 5% compared to less than 1% in the small segments where h_{conv} is calculated.

In [43], the instantaneous and average U -values are calculated using equations similar to [42], obtaining h_{conv} from a dimensionless parameter to be more accurate with regard to the h_{conv} values

tabulated in international standards, using exactly the Nusselt number. As in [42], they assume that the heat flow is in one dimension and horizontal through the walls under study, defining the test conditions and data analysis according to the following international standards [44,45]. In this work, HFM is not necessary and *U*-values are obtained with a deviation of only 1–2% for single-leaf walls and 3–4% for multi-leaf walls under steady state conditions.

Regarding future steps, both [42] and [43] agree that it is necessary to establish a defined value of the minimum temperature difference between the inside and outside of the building, as well as the minimum rate of measurement sampling to obtain reliable *U* results without depending on the type of building under study. In addition, they also highlight that it is required to analyse other types of walls, such as light walls, and different effects of the external weather to validate their methods.

For the case of thermal pathologies, because of their anomalous temperature values with regard to the unaltered surroundings, IRT is an adequate technique for the detection and subsequent computation of some of their thermophysical properties. There are several IRT studies related to the analysis of thermal bridges, due to their severity in buildings. Garrido et al. [39] propose a method for the automatic detection of thermal bridges in different building façades and the automatic computation of their linear thermal transmittance with an image processing approach and in passive mode. Another important pathology is moisture, for which Edis et al. [46] test a quasi-quantitative approach in order to identify rising damp in an adhered ceramic façade, comparing three different thermal data processing techniques, including PCA, and in passive mode. A third pathology is air infiltration, which can account for between 10% and 50% of the energy demand of buildings [47]. In [47], the potential of active IRT is evaluated in both qualitative and quantitative approaches to detect air leakage points within a room.

Table 1 summarizes the IRT works cited in this section together with their main objectives, methodologies and main findings.

Table 1. Review of IRT studies in buildings.

Work [Ref.]	Main Objectives	Methodology	Main Findings
Danielski & Fröling [42]	Description of a quantitative method using IRT to measure the thermal properties of building fabrics in non-steady state	Two stages are performed simultaneously: (i) the first one calculates the convective heat transfer coefficient using an IR camera and three HFMs in a small segment of the building fabric under examination, (ii) the second one evaluates the thermal properties of large building fabrics with an IR camera and indoor temperature sensors	Little variation of results regarding those from a HFM and from literature. For obtaining accurate values, the convective heat transfer coefficient, the solar radiation, the reflected thermal radiation and the number of thermal images were considered as important factors to be taken into account
Tejedor et al. [43]	Presentation of a method to determine in-situ <i>U</i> -values of façades using quantitative internal IRT and under steady state conditions	Instantaneous and average <i>U</i> -values are computed using the proposed numerical model, from data acquired in accordance with international standards	The comparative analysis between measured <i>U</i> -values and theoretical <i>U</i> -values showed maximum deviations of 1.24% to 3.97%, with less execution time required (2–3 h) compared to the HFM method
Garrido et al. [39]	Presentation of a procedure for automatic thermographic building inspections from a quantitative approach, focusing on thermal bridges	First, a rectification of the acquired thermal images is applied. Subsequently, by means of one geometrical and two thermal approaches, the candidates to be a thermal bridge are detected and calculated their linear thermal transmittances from different building façades	15% increase in accuracy for the detection of thermal bridges with regard to existing methodologies, taking into account the false positives and negatives obtained in each methodology

Table 1. Cont.

Work [Ref.]	Main Objectives	Methodology	Main Findings
Edis et al. [46]	Detection of rising damp before visible signs occur using IRT on an adhered ceramic façade	A quasi-quantitative approach, based on time-dependent IRT inspection and thermal images analysis by different data processing techniques: Simple Image Subtraction (SIS), Nonnegative matrix factorization (NMF) and Principal Component Analysis (PCA), is applied on an adhered ceramic façade where rising damp occurs	Comparative assessments showed that the quasi-quantitative approach has great potential to detect changes in moisture and also to eliminate false indications caused by unavoidable reflections and shading, with PCA being the best data processing technique among the three methods tested
Lerma et al. [47]	Evaluation of the potential of active IRT, both in a qualitative and quantitative approach, to detect air leakage points within a room	The qualitative approach consists on comparing the thermal images with those obtained with passive IRT; the quantitative approach is based on the application of different numerical methods in the thermal images	Demonstration that active IRT combined with differences of air pressure is an effective methodology for detecting air infiltration

6.2. Civil Infrastructure

Although IRT applications were not very common in the civil infrastructure field until a few days ago, the use of this technique is now increasing. Proof of this is the existence of different IRT studies applied to different typical materials used in civil infrastructure, such as composite materials, asphalt, metallic materials, concrete and wood materials. Moreover, there are also IRT works that analyse common techniques used during the construction phase of several infrastructures, such as the welding process, and there are also IRT studies that are used for safety issues.

The first IRT applications in the civil infrastructure field were applied to composite materials, within the aeronautical field due to the high exigence in the industry demand. IRT is very useful for analysing this type of material used in airplanes, for example, CFRP, because of its NDT nature in addition to being able to measure in two dimensions and give information in-depth [12]. These characteristics make IRT a useful tool also for other typical materials of infrastructure. Among the most recent IRT works applied to composite materials, Venegas et al. [48] analyse the application of an innovative method for thermographic NDT data processing for the inspection of real aeronautical component, using halogen lamps as thermal stimulation. Another IRT study is the research by He et al. [49], which analyse the barely visible impact damage to CFRPs. In this case, they use one of the advanced thermal excitation techniques, specifically vibrothermography, integrated with nonlinear ultrasound, visualizing the effects on the time domain and frequency domain using the PPT as thermal data processing technique. With a type of laser spot thermography as advanced thermal excitation technique, Montinaro et al. [50] analyse Fibre Metal Laminates (FMLs) with debonded interlaminar layers. Furthermore, IRT has proven advantageous for online monitoring of impact events in several composite materials [51].

Regarding asphalt, there have been many IRT studies applied to pavements. Solla et al. [7] combined Ground Penetrating Radar (GPR) and passive IRT techniques to detect cracks in a road asphalt pavement and characterize their origins. In airport infrastructures, there are the works of Tsubokawa et al. [52] and Moropoulou et al. [53]. In both cases, passive IRT is used to detect defects in pavement, analysing the temperature difference among the pixel values in each thermal image taken.

In the analysis of subsuperficial defects in metallic materials, such as pores, delamination and interior cracks, passive IRT is not recommended, as in the other types of materials of structure, because natural heat sources do not reach the necessary power to penetrate the material under study and

make possible the visualization of the subsuperficial defects by means of the presence of anomalous temperature values in the surface measured with the IR camera [12].

Among IRT works analysing superficial defects in metallic materials, Sakagami et al. [54] develop a new remote non-destructive evaluation technique based on the measurement of both temperature using active IRT, and thermoelastic stress. The temperature measurement is performed for the detection of superficial cracks in a steel plate (with IRT) and, if cracks were detected, the measurement of thermoelastic stress is performed for the evaluation of fatigue cracks propagating from welded joints in steel bridges. Regarding IRT studies analysing subsurface defects, Xu et al. [55] explore the feasibility of using thermoinduction thermography as thermal excitation, in order to detect hidden cracks on corroded metal surfaces without removing the corrosion layer. They use PCA as thermal data processing technique to enhance the features of hidden cracks in the raw thermal images.

Of the IRT works related to concrete and wood materials, we wish to highlight recent IRT studies by Cheng and Shen [56] and Pahlberg et al. [32]. In [56], the authors compare the performance of different thermal data processing techniques in active mode, including PPT and PCA, with that of the conventional static thermal imaging method, to observe which offers the best results in terms of detecting voids in a hollow concrete block during the heating phase. In [32], the authors study the possibility of using ensemble methods, such as random forest and boosting, for the automatic detection of cracks in oak flooring lamellae using ultrasound-excited thermography, an advanced thermal excitation technique, and a variety of predictor variables.

On the other hand, welding process is a common technique for joining parts of an infrastructure, being IRT applied as an analysis tool through the active approach, due to its NDT nature and real-time measurements, allowing high-speed scanning. Rodríguez-Martín et al. [57] performed a simple study of IRT based on the cooling rate of the weld bead in two specimens of low-carbon steel, with a crack and a subsurface crack, respectively, while the authors of [58] present a novel IRT method based on the extraction of isotherms and the rectification of thermal images, allowing the detection and geometric characterization and orientation of two different types of cracks, toe and longitudinal cracks, each belonging to a plaque of low carbon. Within the naval infrastructure, IRT has a high utility due to the large number of welded pieces. For instance, Crupi et al. [59] apply a thermographic analysis to predict the fatigue behaviour of butt-welded joints, made of AH36 steel, which is widely used in shipbuilding.

Finally, IRT is also used for safety issues in the field of civil infrastructure, because the temperature of humans is higher than that of structures [12] and IRT has none of the harmful radiation effects of technologies, such as X-ray imaging, being harmless for humans. For instance, Iwasaky et al. [60] propose an algorithm to detect vehicle positions and their movements using passive IRT.

Table 2 summarizes the IRT works cited in this section together with their main objectives, methodologies and main findings.

Table 2. Review of IRT studies in civil infrastructures.

Work [Ref.]	Main Objectives	Methodology	Main Findings
Venegas et al. [48]	Application of an innovative method for thermographic NDT data processing to inspections on real aeronautical components	A 3D thermal diffusion model is applied in one of the coordinate planes in order to obtain the thermal diffusivity values in several samples	Improvement of the analysis of the behaviour of the thermal flow, increasing the Signal-to-Noise-Ratio (SNR) of the initial temperature from more than 15% up to 50%, reducing the content of noise and the irregularities in the stimulation process
He et al. [49]	Inspection of barely visible impact damage in CFRP, integrating vibrothermography and nonlinear ultrasound as thermal stimulation	A time domain analysis and PPT are employed to process the sequence of thermal images	The barely visible impact damage could be detected by the method developed, not being detected by visual inspection or machine vision
Montinaro et al. [50]	Analysis of FMLs with debonded interlaminar layers, using a type of laser spot thermography (flying laser spot thermography) as thermal excitation	Flying laser spot thermography technique is simulated by means of a Finite Element Analysis in order to better identify the mechanisms leading to the formation of the defect signature. To validate the numerical solution, the heat propagation over a single aluminum layer is compared with an available analytical solution	A better sensitivity is obtained with this method for the analysis of debonded layers with regard to existing methodologies
Solla et al. [7]	Detection of cracks in road pavement and characterization of their origins through the combined application of GPR and IRT	First, the techniques used are calibrated under controlled conditions. Subsequently, field data are acquired with both techniques and validated against calibration	Suitability of the combination of techniques for the inspection and characterization of cracks in asphalt, allowing for the estimation of the depth of crack, the detection of the presence of filling material and the preliminary identification of the origins and severity of the cracks
Tsubokawa et al. [52]	Inspection of the debonded layers from the flexible pavement of an airport using IRT	An analysis of the surface temperature difference among the pixel values of the thermal images taken from a height of 10 m and every 30 min from 0:30 a.m. to 5:30 a.m. is performed	Verification of the applicability of IRT for detecting layer debonding at the depth of 40–70 mm

Table 2. Cont.

Work [Ref.]	Main Objectives	Methodology	Main Findings
Moropoulou et al. [53]	Detection of delamination in asphalt pavement at an airport using IRT	Analysis of the surface temperature difference from the histograms of the thermal images taken during daytime	Detection of cracks, flaws and other imperfections is achieved satisfactorily
Sakagami et al. [54]	Development of a new remote non-destructive evaluation technique combining temperature measurement by IRT and the measurement of the thermoelastic stress, for the evaluation of fatigue cracks propagating from welded joints in steel bridges	A self-reference lock-in data-processing technique is developed to improve the SNR of the thermal images obtained in the crack detection process. Thermoelastic stress analysis in the vicinity of crack tips is performed after the crack detection process	Fracture mechanics parameters could be evaluated with good accuracy for enabling the assessment of structural integrity based on the mechanical parameters of the evaluated fracture (stress intensity factors K_I and K_{II} for mixed-mode cracks)
Xu et al. [55]	Investigation on thermoinduction thermography to detect hidden cracks on corroded metal surface without removing the corrosion layer	The experiments are performed on a metallic bar with three hidden cracks and the validity of thermoinduction thermography is verified with the analysis of thermal images and thermal responses. PCA is applied to enhance the features of hidden cracks in the raw thermal images by eliminating the effects of uneven corrosion and non-uniform heating	The combination of thermoinduction thermography and PCA has provided a convenient and effective way to detect hidden cracks on corroded metal surface
Cheng & Shen [56]	Comparison of different thermal data processing techniques, including PPT and PCA, with that of the conventional static thermal imaging method, with the purpose of detecting voids in a hollow concrete block during the heating phase	The temperature evolution of hollow concrete block under artificial heating is investigated studied in each of the techniques for subsequent comparison	By comparing the SNR results, a significant improvement can be found when using the thermal data processing techniques
Pahlberg et al. [32]	Use of ensemble methods: random forests and boosting, for the automatic detection of cracks in oak flooring lamellae using ultrasound-excited thermography and a variety of predictor variables	Several image processing techniques are used to suppress noise and enhance probable cracks in the thermal images under study before being used in the ensemble methods	The classification accuracy is significantly improved from previous research through added image processing, introduction of more predictors, and by using automated machine learning

Table 2. Cont.

Work [Ref.]	Main Objectives	Methodology	Main Findings
Rodríguez-Martín et al. [57]	Application of an inexpensive and versatile thermographic test for the detection of subsurface cracks in welding	First, a study of the cooling tendencies in the defect and the non-defect zone is performed in order to detect this pathology, from the thermal images taken in the cooling process monitoring. Subsequently, a contour lines algorithm is applied to the detected defects in order to define their morphologies	Satisfactory differentiation between two types of cracks: toe crack and subsuperficial crack, as defined in the quality standards
Rodríguez-Martín et al. [58]	Description of a novel IRT method for the detection and geometric characterization of cracks in welding	A photogrammetric technique, image rectification, is applied in each thermal image obtained after the application of a simple excitation source to the surface of the welding. Then, a contour lines algorithm is implemented, generating isotherms in the images under study	A fast and simple detection and assessment of the morphology of two types of cracks, toe and longitudinal, is achieved satisfactorily, with an error rate of 1.11% and 29.94% in length and width regarding the toe crack, and an error rate of 2.5% and 64.06% in length and width regarding the longitudinal crack
Crupi et al. [59]	Prediction of the fatigue behaviour of butt welded joints using the Thermographic Method (TM)	The TM, based on thermographic analysis, is performed in order to assess the fatigue capability of butt welded AH36 steel joints, in terms of Stress (S), Number of cycles (N) curves and fatigue limits	Demonstration of the ability of the TM to assess the fatigue limit of steel welded joints and the entire S-N curve, obtaining reliable results in a very short time compared to traditional fatigue tests
Iwasaky et al. [60]	Development of an algorithm for the detection of vehicle positions and movements using IRT	The proposed algorithm specifies the area of moving vehicles based on the standard deviations of the pixel values along the time direction of the spatiotemporal image sequences. Moreover, vehicle positions are found by applying a pattern recognition algorithm that uses Haar-like features per frame of the images	96.2% accuracy in vehicle detection

6.3. Heritage Sites

Heritage goods can be found either buried, disintegrated, or partially intact. Regarding buried goods, IRT is a useful technique in case subsurface air cavities are created by the air trapped in the buried structures, having different thermal signatures than those of unaltered soil [12]. Lunden [61] uses aerial thermography applied to the detection of archaeological remains buried at a site in Dalecarlia, Sweden, in passive mode.

Regarding the partially intact heritage goods, the aim of IRT is to evaluate their level of decay, for the purpose of performing activities of restoration and conservation. It is very important to detect defects at an early stage, and to understand the modifications due to the variation of environmental parameters, to develop the most suitable plan to prevent the decomposition of heritage goods. Meola [62] controls microclimatic conditions in order to maintain various masonry structures in good conditions, with active IRT. On the other hand, Tavukçuoğlu et al. [63] assess in situ cracks in historic masonry structures through quantitative IRT, in active mode, and Sfarra et al. [8] evaluate defects in a panel painting by combining Holographic Interferometry (HI), active IRT, using TSR, PCA and PPT as thermal data processing techniques; and Ultrasonic techniques. HI technique is one of the most common and versatile method used in artwork diagnostics, since discontinuities such as cracks, voids or delamination appear as an anomaly in a regular interferometric fringe pattern and, therefore, allow the identification of the fault region. Tornari et al. [64] also combine HI and active IRT for cultural heritage structural diagnostic, showing highly complementary properties in the information provided with regard to the structural understanding of surface and defect reaction under transient excitation, especially for aged marquetry and fresco sample. On the other hand, Ultrasonic technique is widely applied in the evaluation of the wood quality in several characterization procedures, for diagnostic purposes and for the classification in working conditions. For instance, in [8] is used to differentiate natural and artificial defects and, in more recent works, Zhang et al. [65] use IRT and Ultrasonic C-scan to investigate basalt fiber reinforced polymer, CFRP and basalt-carbon fiber hybrid specimens subjected to impact loading. With the application of the Ultrasonic C-scan technique, the delaminated areas of the different specimens caused by the different levels of impact are observed.

Table 3 summarizes the IRT works cited in this section together with their main objectives, methodologies and main findings.

Table 3. Review of IRT studies in heritage sites.

Work [Ref.]	Main Objectives	Methodology	Main Findings
Lunden [61]	Detection of archaeological remains buried by aerial thermography	Thermal imaging of an archaeological site from a helicopter	Variations in temperature have been observed in the thermal images, which could be related to the archaeological remains found later
Meola [62]	Application of IRT to the inspection of architectonic structures and works of art	Use of the LT technique to evaluate the Archaeological Museum of Naples and in the archaeological site of Pompeii	The variation of the phase angle with varying heating frequencies provided useful information to discriminate between tiles made of different materials, to locate debonded tiles and detachments in the plaster support underneath the tiles, and to discover restored plaster in areas without tiles
Tavukçuoğlu et al. [63]	In situ assessment of cracks in historic masonry structures by quantitative IRT	First, the superficial and deep cracks in various masonries were exposed to heating conditions. Subsequently, the temperature evolution in time under heating and then cooling exposure conditions was examined by IRT analysis	The results of thermal monitoring during the exposure of the heating and cooling conditions provided hints to quantitative IRT methods for the depth assessment of deep cracks in masonry
Sfarra et al. [8]	Demonstration of the potential advantages of combining Holographic Interferometry, IRT and Ultrasonic techniques for structural diagnostics of a wooden panel painting	First, Holographic Interferometry is used to determine the regions of interest of the panel painting. Subsequently, detailed research is performed in those regions using IRT and the Ultrasonic techniques. In IRT, TSR, PCA and PPT are used as data processing techniques	Confirmation that Holographic Interferometry provided the surface and subsurface information belonging to the panel painting under study, being possible to combine it with IRT and Ultrasonic techniques to identify the nature of the subsurface defects, such as detached regions and micro-cracks
Tornari et al. [64]	Combination of HI and IRT for the cultural heritage structural diagnostic	Several experiments with HI and IRT are performed under laboratory conditions	Results confirm the effectiveness of each technique alone and the combination of data of both techniques in the conservation field
Zhang et al. [65]	Comparison of IR and Ultrasonic C-scan to investigate basalt fiber reinforced polymer, CFRP and basalt-carbon fiber hybrid specimens subjected to impact loading	Three different impact energies are applied for the evaluation of the impact damage level in the different samples	With the application of the Ultrasonic C-scan technique, the delaminated areas of the different specimens caused by the different levels of impact are observed

7. Conclusions

IRT is a non-destructive technique that measures the radiation emitted by bodies in the thermal infrared band of the electromagnetic spectrum. The thermal sensor of an IR camera performs this measurement, converting thermal radiation to temperature values. Each value is assigned to one pixel of the image obtained from the IR camera as final step. The Stefan-Boltzmann law is used to calculate the radiation-temperature conversion, knowing certain influencing factors beforehand.

Since a thermal pathology has a different thermal behaviour, and therefore a different temperature value, with regard to its unaltered surroundings in a specific infrastructure, IRT is an useful tool for inspecting different types of infrastructures through the different existing IRT approaches: passive/active and qualitative/quantitative. Therefore, this paper reviews several IRT applications to infrastructure inspections, classifying the studies into three main application groups: buildings, civil infrastructure and heritage sites. Prior to that, the theory, different approaches, the advantages and restrictions and the latest thermal data processing techniques of the IRT method were explained in four different sections.

It was observed that, in addition to detecting and characterizing the possible thermal pathologies of an infrastructure, IRT can also thermally characterize the properties of the materials composing the structure, such as overall heat transfer coefficient, in order to estimate the real energy demand of a residential building, for example.

As a conclusion, this work demonstrates the utility of the IRT technique in a wide variety of objectives and infrastructures, including the analysis of defects up to a certain depth. However, there is still work to be done, and one of the fields that should be studied, with regard to future IRT research, is the automation of the interpretation for infrastructure inspections, as in [37,39,40], in order to minimize the risk of missing or misinterpreting thermal pathologies present in the infrastructure under study.

Funding: The authors would like to thank the Ministerio de Economía y Competitividad (Gobierno de España) for the financial support given through programs for human resources (FPU16/03950). Special thanks to the Cátedra Iberdrola VIII Centenario–University of Salamanca, and European Commission for the funding given through the program H2020-FTIPilot-2015-1 to the proposal 720661–ENGINECY.

Conflicts of Interest: The authors declare no conflict of interest.

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