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REVIEW PAPER

Active infrared thermography applied to the investigation of art and historic artefacts

**F. Mercuri · U. Zammit · N. Orazi ·
S. Paoloni · M. Marinelli · F. Scudieri**

Cultural Heritage Special Chapter

Abstract Infrared thermography (IRT) is a non-destructive technique that has recently been extensively applied to the investigation of cultural heritage. It provides information on the surface and subsurface structure of the artefacts by the analysis of the heat diffusion process within the sample. IRT has been successfully applied to the study of historic large structures and buildings most of the time by means of the so-called *passive* approach, where only the naturally occurring temperature changes in the sample are analysed. On the other hand, IRT has also been applied to the study of other art and historic artefact by applying the so-called *active* method where the thermal stimulation of the sample is required. In this article, an overview of the applications of active thermography to the investigation of art and historic artefacts will be presented and discussed.

Keywords Active infrared thermography · NDT · Cultural heritage

Introduction

One of the main aspects of the conservation science is the assessment of the preservation state of the artefacts. The degradation of their material, in particular, is usually evaluated by quantifying the change induced in some of its physical properties. Thermal parameters like, for instance, the specific heat and the thermal diffusivity have, in fact, been shown to be affected by the deterioration processes, and their measurement thus provides a tool for monitoring the degradation dynamics in the investigated material [1]. In that respect, a number of different thermal method have been applied to the characterization of cultural heritage material [2–7]. Beside the material characterization, the analysis of the structure of an artefact is also often fundamental in order to assess its preservation state. In that regard, the most common requirement for the investigations in the field of cultural heritage is that the employed technique must be non-destructive, possibly providing information in the form of imaging which can readily be interpreted.

The infrared thermography (IRT) is a technique currently used for the non-destructive characterizations in a large variety of different fields and, during the last two decades, in particular, it has evolved into a powerful non-destructive tool for the study of the conservation of cultural heritage. The success of the IRT for this kind of applications is based on a number of reasons, such as its non-destructive nature, the possibility to be used in situ, the capability to perform both qualitative investigation of surface and subsurface structure of the artefacts and the quantitative analysis of the thermal transport quantities of its constituent materials. The IRT provides images, in the form of temperature maps, that reveal features of the subsurface structure and inhomogeneities in the material. Through such images, specific areas of the sample can be identified where evaluation of the thermal diffusivity and/or further analysis with different techniques can be performed.

IRT investigations are carried out typically according to two distinct methods, usually indicated as *passive* and *active* thermography.

In the passive method, the temperature is monitored without employing any heating of the sample induced by

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F. Mercuri (✉) · U. Zammit · N. Orazi · S. Paoloni ·
M. Marinelli · F. Scudieri
Dipartimento di Ingegneria Meccanica, Università di Roma “Tor Vergata”, Via del Politecnico 1, 00133 Rome, Italy
e-mail: mercuri@uniroma2.it

the measurement procedure. Features of the temperature distribution, like differences with respect to a reference level, allow to obtain qualitative information about the specimen under examination. In passive IRT, the temperature differences are originated by thermal phenomena occurring naturally in the system under investigation. For example, damp patches over walls can be detected since they are colder because of the evaporation of the moisture. Reading of the masonry texture under the plaster and the detection of hidden architecture elements in general can also be investigated thanks to the heat diffusion through the building walls induced by the daily cycle of change of temperature. This explains why many historic structures and ancient buildings have been studied by the passive thermography [8, 9].

Active IRT, on the other hand, allows to obtain both qualitative and quantitative evaluations by monitoring the transient of the temperature change induced in the artefacts by means of adequate artificial heating usually produced by the absorption of the light emitted by flashed or dc lamps, lasers or other light sources. In this article, an overview of the applications of the active thermography to art and historic artefacts will be presented. It will be done by reviewing a number of studies reported in the literature that have been classified in three different categories: books and documents, archaeological findings and artworks. Finally, the perspective of IRT developments for applications in the field of cultural heritage and its integration with other techniques will be also discussed.

Active infrared thermography

In a typical active IRT analysis, the infrared radiation locally emitted from the surface of a sample which has been stimulated by a thermal perturbation is detected by means of an infrared camera which provides images, known as thermograms. These are maps describing the spatial distribution of the amount of the IR radiation coming from the different parts of the sample. According to the Stefan-Boltzmann law, such a quantity is directly proportional to the fourth power of the emitting body temperature so that thermograms simply represent maps of the temperature distribution at the sample surface.[1] Such images are provided in a grey or colour scales and are usually processed to reveal features of the surface and subsurface structure and composition. In fact, the heat diffusion process taking place through the sample volume will be uniform in the case of a homogeneous material giving rise to a homogeneous evolution of the temperature distribution at the sample surface. On the other hand, the presence of inhomogeneities, at or beneath the surface, locally affects the heat propagation and results in a localized temperature difference (thermal contrast). The subsurface inhomogeneities can be related to the material composition, the interfaces of the different components in assembled structures or the presence of inclusions or defects like cracks, voids, detachments, flaking, etc. The analysis of the temperature distributions at the surface allows also to retrieve quantitative information on some of the physical properties of the material, related to the thermal transport, in particular, and to characterize those features the imaging had revealed. It is worthwhile pointing out that the quality of the results the IRT provides depends on the sample surface properties that could limit the capability of the technique. The surface finish, roughness, cleanliness and other surface conditions can entail variation of the IR emissivity, a surface coefficient which characterizes the emission efficiency of the infrared radiation and which plays an important role in the IRT signal generation [10]. To overcome the problem of weak and/or inhomogeneous values of the emissivity, different solutions have been proposed, such as the coating of the sample surfaces with removable colloidal graphite [11]. This kind of treatment is not always advisable on a cultural heritage specimen so that, for each specific artefact, adequate solutions must be sought [12].

A large number of active IRT configurations and set-ups have been employed in the various investigations performed on the cultural heritage the two main ones being the *pulsed* IRT and the *lock-in* IRT that will be briefly described hereafter.

Pulsed infrared thermography

Pulsed IRT basically consists in heating the sample for a short-time interval, lasting typically a few milliseconds, and then detecting the temperature evolution with time. Heating is usually obtained by means of flash lamps whose power is eventually limited in order to prevent damage in the sample. The temperature distribution immediately following the pulse, which can reach at most a few degrees, is considered pretty uniform across the sample area and, consequently, the heat diffusion takes place predominantly along a direction orthogonal to the sample surface. If one considers heating and detection occurring at the same sample surface (reflection configuration), the following evolution takes place. After the heating excitation, the temperature rise ΔT at a given point of the sample surface diminishes with time t, due to the heat diffusion into the sample, according to the expression [13, 14]

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[1] It must be pointed out that in IR thermography analysis, the term thermogram is currently used to indicate an image of the temperature distribution of the sample surface in spite of the fact that the same term is used also to indicate the vs temperature thermal response of a sample in a Differential Scanning Calorimeter scan.

$$\Delta T(t) = \frac{Q}{e\sqrt{\pi t}} \qquad (1)$$

where Q is the applied heating energy and $e = \sqrt{\rho k c}$ is the sample thermal effusivity being ρ, k and c, respectively, the density, the thermal conductivity and the specific heat. The effect of subsurface inhomogeneities in the thermal properties due, for instance, to localized defects is to modify the temperature diffusion rate which deviates form its expected $t^{-1/2}$ time dependence. Therefore, when monitoring the surface temperature, inhomogeneities show up as areas of different temperature with respect to the homogeneous parts of the sample. In particular, such a circumstance makes it possible to attain information on subsurface structures during the investigation of assembled artefacts. Different information on defects like its position or size can be estimated by a careful analysis of $\Delta T(t)$ as proposed in several methods which can be found in the literature [13].

In addition to structure investigation, pulsed IRT allows the evaluation of the thermal diffusivity of the sample along a direction orthogonal to the sample surface. In fact, when investigating finite thickness samples, once the thermal front reaches the rear surface, further heat diffusion is practically inhibited due to the poor thermal transport properties of the surrounding air and, consequently, $\Delta T(t)$ approaches a nearly stationary value. Therefore, when the evolution of $\Delta T(t)$ is reported in a log–log plot, two asymptotic regimes, consisting of a line of slope $-1/2$ during the early stages followed by a horizontal plateau, can be readily identified (Fig. 1).

The intersection of these lines reveals a characteristic time [13]

$$t_c = \frac{L^2}{\pi D}, \qquad (2)$$

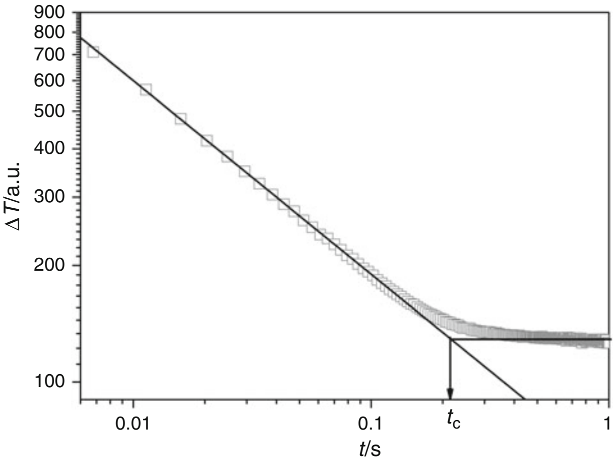


Fig. 1 Pulsed IRT. Temperature decay versus time following the heat pulse. The intersection of the two linear regimes defines the characteristic (crossing) time providing the thermal diffusivity value of a parchment sample in the direction across the leaf section [1]

where L is the sample thickness and $D = \frac{k}{\rho c}$ is the thermal diffusivity, thus enabling the determination of D provided that L is known. On the other hand, L can be estimated by means of Eq. 2 once the sample thermal diffusivity D has been determined thus providing a useful tool for the evaluation of the sample thickness.

The considerations reported above apply also for other pulsed ITR configurations, like the transmission one, where heating and detection occur on the opposite surfaces of the sample. In this case, after the application of the heating pulse, $\Delta T(t)$ increases till reaching a nearly stationary value. In this case another characteristic time [15]

$$t_{1/2} = 0.139\frac{L^2}{D} \qquad (3)$$

can be determined, being $t_{1/2}$ the time for $\Delta T(t)$ to reach half of its maximum value, from which once again the evaluation of D, if L is known, can be carried out.

The above mentioned IRT pulsed configuration is limited to the thermal parameter evaluation in finite thickness samples. In order to overcome such limitation, other IRT configurations have been developed where, for example, the sample is time heated locally by a focused light beam [16]. By analysing the time evolution of the surface temperature distribution, thermal diffusivity can be locally evaluated also on very thick objects. For instance, such an approach has been used for the investigation of different types of limestone [17].Among pulsed IRT techniques, the *step heating* method can also be included as a limit case for indefinitely long pulses. With such a method, the increase in surface temperature is detected as function of time following a constant heating power provided to the sample surface at a given initial time [18]. Such a technique allows the investigation of the sample structure over a larger depth in comparison with other short-pulsed techniques also providing the possibility of inducing a smaller temperature rise in the sample.

Lock-in infrared thermography

In the *lock-in* IRT, the sample is periodically heated to generate a field of temperature oscillations known as thermal waves. These are then detected by a synchronized IR camera according to the lock-in processing technique. As a result, the amplitude and phase images of the oscillating temperature field are retrieved. In particular, the phase image, which is associated with the thermal wave propagation time, is independent of the optical properties of the sample and, consequently, it is not affected by any possible local difference in the emissivity or light absorption which, on the contrary, strongly influence the amplitude images. Consequently, the phase image constitutes a useful tool for reliable quantitative characterizations.

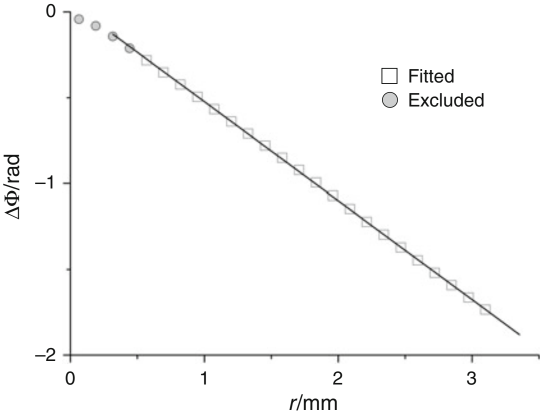


Fig. 2 Lock-in IRT. Phase change versus lateral distance from the periodically heated spot. The obtained data slope allows the thermal diffusivity determination along the leaf plane of the same parchment sample as in Fig. 1 [1]

It is worthwhile to note that the lock-in synchronous detection selects the thermal waves diffusing into the sample over a distance of the order of the thermal diffusion length $\mu = \sqrt{\frac{D}{\pi f}}$, where f is the heating modulation frequency. As a consequence, by properly tuning the frequency, it is possible to vary the propagation distance μ and hence to probe the sample over different depths. The analysis of the images obtained for different f allows to detect subsurface defects with a larger sensitivity in comparison with the pulsed IRT techniques, which, on the other hand, are less time consuming.

Among the different applications, the lock-in technique allows the prompt evaluation of the in-plane thermal diffusivity, along any given direction parallel to the sample surface, from the analysis of the slope of the asymptotic linear dependence $\Phi(r) = \Phi_0 - \frac{r}{\mu}$ of the phase as function of the later offset r from the heated spot (Fig. 2).

Finally, it is also worth mentioning the *pulsed phase* IRT technique which is also widely used in the inspection of artwork [19]. The heating pulse can be mathematically viewed as composed by a continuous superposition of harmonically oscillating excitations whose frequency extends over a range of the order of the inverse of the pulse duration. Therefore, by carrying out pulsed IRT measurements, the frequency dependence of the sample thermal wave response can be retrieved from the Fourier analysis of the temperature transient.

Applications

The active thermography has been applied to the investigation of various kind of artefacts, composed by substantially different structures and materials. Hereafter, an overview of various applications is presented, ordered according to those three main cultural heritage areas: books and documents, archaeological findings, and artworks.

Books and documents

The thermal analysis has been often used to investigate the preservation state of different library and archive materials. Collagen-based materials like leather and parchment, for instance, have been recently studied by differential scanning calorimetry (DSC) and other thermal methods [20, 21]. Under heating, collagen can denature and loose its characteristic structure. Such denaturation process has been studied in structured parchment samples with different equilibrium moisture content [22, 23] or in defibrated samples fully hydrated in excess water condition [1]. In particular, for a given hydration condition, the specific heat versus temperature behaviour shows a peak associated to the collagen denaturation process whose shape and position depend on the degree of degradation of the material. The peak temperature position decreases with deterioration, while the width of the peaks can be related to the homogeneity of the preservation state of the analysed material [24].

Recently, it has been shown that not only static thermal parameters, like the specific heat, but also dynamic quantities, like the thermal diffusivity, provide useful information to characterize the structure and the microstructure of library material and its preservation state. In this frame, IRT has proven to be a powerful tool for such kind of investigation due to its capability to simultaneously combine the measurement of thermal diffusivity with the thermal imaging which can indicate those areas of interest where to perform the quantitative analysis. Since the beginning of the last decade, historical parchment bindings have been studied by means of the IRT which was capable to provide information on both the assembled structure and the single component materials. In the bookbinding analysis, the thermographic imaging allowed to detect the presence of damage and to investigate the adhesion state of the different parts and the techniques employed for the assembly of the different binding components [12].

In this kind of artefacts, parchment is one of the most important materials to be studied and the anisotropic nature of its fibres microstructure is reflected in the corresponding different thermal diffusivity values that can be measured by IRT along different directions and, in particular, along and across the leaf extension, respectively. Figure 3 shows the thermal diffusivity values obtained along both such directions on four differently aged samples of a recently manufactured parchment. The data show that the values are larger along the leaf plane and that the deterioration processes reduces such values diminishing the anisotropy in the thermal diffusivity [1].

Finally, it is worth mentioning that IRT has been also employed to study the effects of ink inclusion in the parchment and to characterize defects like micro fractures and flaking in its structure [25].

As an example of the above mentioned investigations, in Fig. 4 two thermograms of a seventeenth century volume with limp parchment cover are shown. In such kind of bookbinding, the external cover is not supported by a rigid board and the turn-ins consist of the parchment leaf being folded onto its rear side. The quality of the contact is revealed by the different grey levels in the image. The darker parts correspond to those areas where, thanks to the good contact between the external cover and turn-in, the heat diffusion is more efficient and the surface cools down faster. The elements in contact with the rear side of the cover are the headbands and bands (framed in Fig. 4a, b) and their hidden paths indicated by the arrows.

The image in Fig. 5a refers to a seventeenth-century volume. The photograph in Fig. 5a shows the hardback cover of the book, made of two ancient manuscript paper sheets glued together. The thermogram of Fig. 5b reveals a good contact area between the cover leaf and the underlying paperboard that has been put into evidence by the dashed curve.

The outer area appears lighter due to thermal barrier to the heat diffusion which is constituted by the interstitial air found in the detached areas no longer in contact with the board. In Fig. 5c, the spine of the volume is shown. Its thermogram in Fig. 5d shows the bands and the headbands under the paper cover.

The thermograms in Figs. 4 and 5 have been obtained by the pulsed IRT, heating the samples with two 3 kW lamps, where the UV component was filtered out, and which induced a temperature increase smaller than 1 °C.

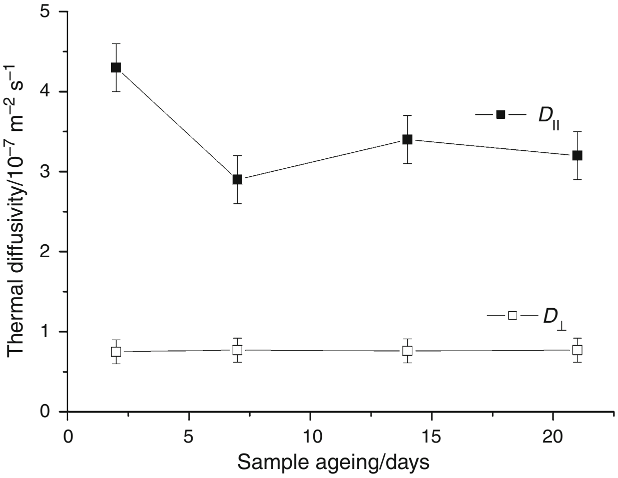


Fig. 3 Thermal diffusivity (*D*) values of four differently aged samples of recently manufactured parchment, measured along (||) and across (⊥) the leaf extension [1]

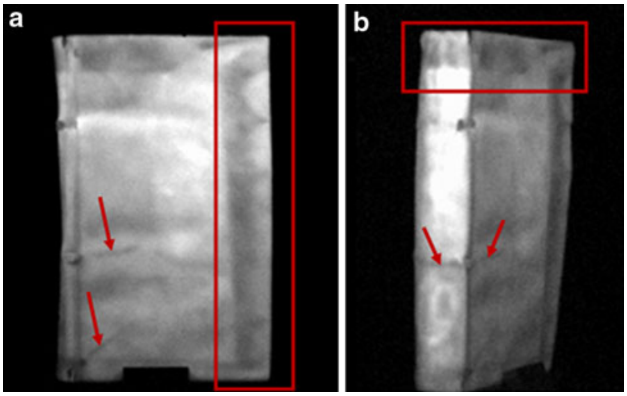


Fig. 4 Thermograms of side view **a** and oblique view **b** of a seventeenth century volume revealing headbands and bands (framed) and the hidden paths indicated by the *arrows*

The features of ~1 mm can be resolved in such thermograms, thanks to both the capability of the employed camera (CEDIP Jade MWIR having a focal plane array of 320 × 240 elements and e temperature resolution of 0.02 K) and the magnification chosen in consideration of the extension of the artefact area to be framed.

Archaeological findings

In the archaeological field, thermography has been widely used with the passive approach for the investigation of historic buildings [8, 9] and the in situ inspection of structures inside important archaeological sites [26, 27]. On the other hand, a number of applications of the active IRT to the study of movable archaeological artefacts have also been reported in the literature. For such an application, the IRT investigation is often performed quantitatively providing measurements of the thermal diffusivity or thickness [11, 12, 28]. That is the case, for instance, of the analysis of the artefact whose picture is shown in Fig. 6a and which consists of a V century B.C. Greek ceramic. The image in Fig. 6b shows a thickness map of a fragment of the pot, obtained by pulsed IRT. The thickness map was obtained by associating to every point (pixel) of the image the local thickness value obtained from the analysis of the characteristic times, referred to in Eqs. 2 or 3, once the thermal diffusivity value is known.

For the map in Fig. 6b, the mean value of the thermal diffusivity, $D = 4.77 \times 10^{-7}\ \mathrm{m}^2\ \mathrm{s}^{-1}$, had been previously determined by several measurements performed by the pulsed IRT in different configurations and was assumed uniform throughout the sample [28]. A further case, studied by the authors of the present paper, concerns the Roman terracotta whose thermograms are shown in Fig. 7. The artefact consists in the neck of a Roman amphora recovered from the see bed. Its surface has been analysed in order to characterize the nature of the concretions and, among them,

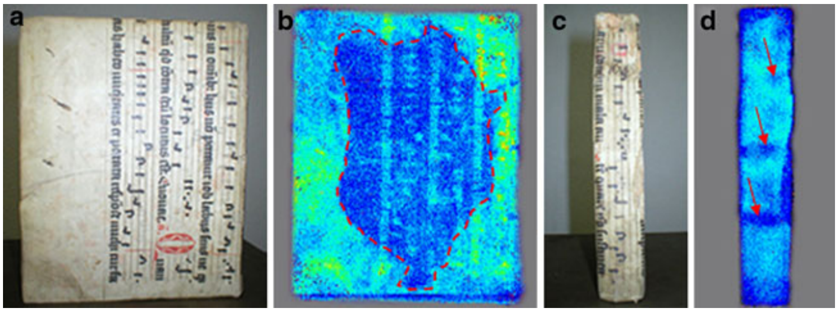


Fig. 5 Thermogram of a seventeenth century volume. The *dashed line marks*, in the back cover, the *darker* area in good contact with the board. The *lighter* outer area reveals a detachment of the material from the underlying board

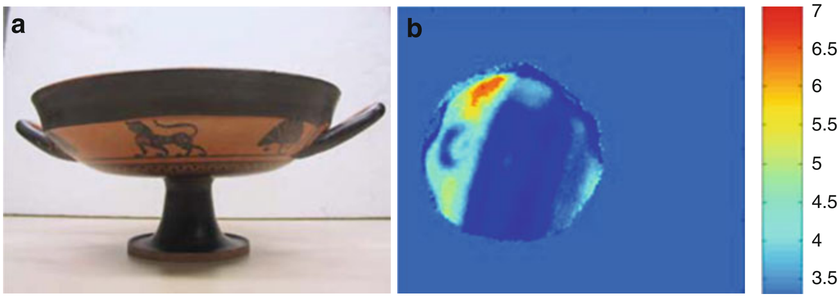


Fig. 6 Photograph **a** of a Greek ceramic and thickness (mm) map of a fragment of the pot **b** obtained by pulsed thermography [28]

the tracks left by various molluscs. In this respect, the adhesion between the two shells (indicated by the arrows) and the earthenware was monitored in order to establish whether a preformed concretion interface was present under the shell or if they were directly anchored onto the underlaying earthenware.

The sample was heated by means of three 3 kW lamps. The reported thermograms (a) and (b) have been taken 0.02 s and 2 s after the light pulse, respectively. The thermogram (a) shows that during the early stage of the decay the two shells have similar temperature values (same colour), quite different with respect to the one of the amphora material. The subsequent thermograph (b) shows that at later times the shell at the top appears hotter (lighter colour) than the bottom one. The former stays warm longer because of the presence of a preformed concretion layer beneath the shell, acting as a barrier for the heat diffusing to the amphora. The latter shell, on the other hand, cools more rapidly because heat diffuses more easily to the amphora, indicating a direct contact with the amphora itself.

Pulsed IRT has been also applied to the study of metal findings. Three examples of this kind concerning Phoenician-Punic jewels and Roman coins were reported in Ref. [11]. The images in Fig. 8 refer to a silver, gold laminated, Phoenician earring. The photograph in Fig. 8a shows the coil of a drawn gold wire having a decorative and/or structural role. An enlarged detail of the coil is shown in the image of Fig. 8c, obtained by scanning electron microscopy and revealing the typical deformation traces consequent to the wire drawing. The purpose of the analysis was to characterize the adherence of the wire on the underlying structure. In this respect, the thermogram in Fig. 8b put into evidence those segments of the wire which are brighter in colour. They correspond to the parts of the coil where the mechanical contact between the gold wire and its support is poor possibly also due to the local deformations introduced by the drawing of the wire. In the thermogram of Fig. 8b, using the same apparatus described above in the discussion of Fig. 5 and choosing a suitable magnification, some components of the earring like the wires having a 0.2 mm section can be resolved.

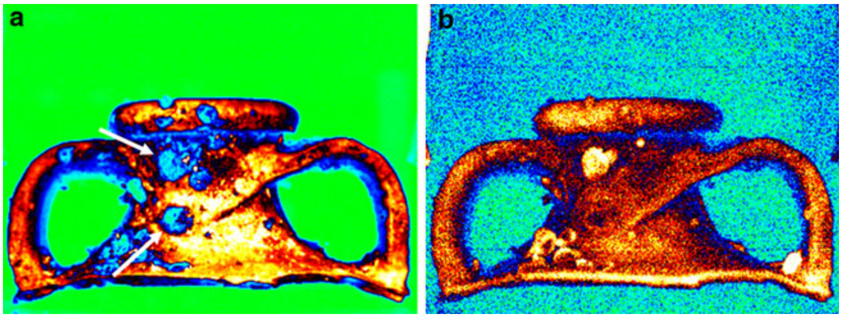


Fig. 7 Thermograms of a Roman terracotta. Thermogram **a** shows that, 0.02 s after the light pulse, the two shells indicated by the *arrows* have the same temperature (same colour). In the thermogram **b** obtained 2 s after the pulse, the shell at the top appears warmer revealing a concretion interlayer between the shell and the earthenware

In Fig. 9a and b, the photograph and the corresponding thermogram of a gold laminated Phoenician-Punic silver ring are reported. It should be mentioned that the collect had been first welded onto the ring, and a gold leaf was then applied on top of the welding material. The brighter areas shown in the thermogram reveal the presence of the welding material, beneath the gold leaf.

Finally, Fig. 10a and b shows the photograph and the corresponding thermogram of a first century A.D. manufactured Roman bronze coin. The thermograms was been taken during the cooling phase of a pulsed IRT measurement and shows two distinct areas, area (A) appearing colder than area (B). The two different areas correspond to the difference in the coin composition and in the surface porosity probably due to different preservation state. All this caused differences in the effective thermal diffusivity in the two areas which lead to different values of the local temperature [11].

Artworks

A number of investigations performed by active thermography on different artworks like mosaics, paintings and bronzes [29] have also been reported in the literature and are hereafter reviewed.

Mosaics

A mosaic is a layered structure. Beneath the external layer of *tesserae*, the setting bed, the plaster and the supporting wall are found. The most important structural defects are the detachment or adhesion loss between the *tesserae* and the setting bed, the detachment between the setting bed and the plaster and between the plaster and the wall. Thermography has been proposed to characterize defects in such layers and it has been tested for the detection of buried plastered mosaics [30]. Avdelidis et al. using different transient approaches have tested various kind of suitably prepared panels of different mosaics with gold or marble tesserae, covered with plasters of various thickness and composition [31]. Mazioud et al. performed both numerical simulation and experimental investigation on laboratory samples to study the capability of the IRT to reveal mosaic areas buried under the plaster and to detect the joints between some polystyrene *tesserae* [32]. Based on the analysed materials and geometries, the above mentioned studies have shown that, while mosaics can be fruitfully detected by IRT, the plaster joints cannot be revealed by simply detecting the temperature maps (Fig. 11) but are barely detectable only after adequate processing of the raw temperature profiles.

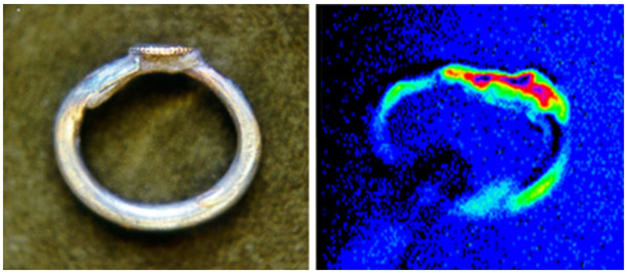


Fig. 9 Photograph **a** and thermogram **b** of a Phoenicians ring revealing the material used to weld the collet to the support

It is worthwhile noticing that same transient analysis (like the *cooling-down* thermography [31]) requires the sample to be heated for a relatively long time, up to 1 h or more, leading to a possible excessive supply of heat which may damage the artefact. Particular care must be then taken when real cultural heritage is analysed.

Paintings

The study of paintings was one of the earliest applications of the thermography to the investigation of artworks. Among many kind of paintings, the most relevant investigations have been performed on frescoes, canvas and woods. In fact, being this technique able to investigate the surface and sub-surface features of a layered structure, it represents an efficient way to retrieve information concerning the adhesion of the paintings to the support, the painting thickness, the canvas and wood texture, cracks, detachments and inclusions in the fresco plaster, etc.

Frescoes In the analysis of frescoes, the local evaluation of the thermal properties and the temperature mapping represents a useful tool for the investigation of their

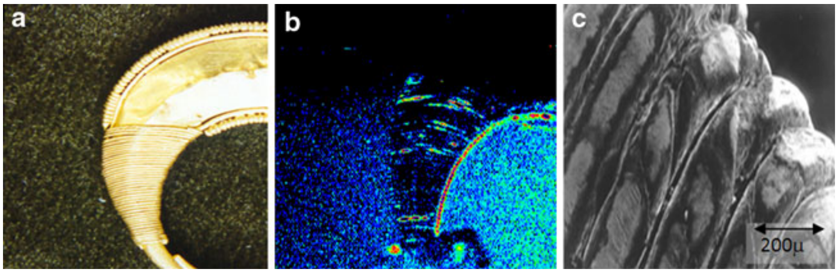
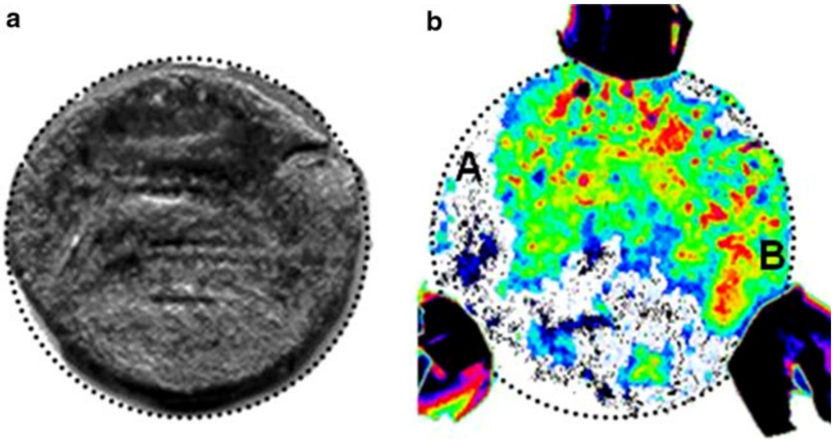


Fig. 8 Photograph **a** and thermogram **b** of a Phoenicians earring revealing the parts of poorer mechanical contact between the gold wire coil and its support. **c** Image obtained by scanning electron microscopy showing defects of the wire drawing

Fig. 10 Photograph **a** and thermogram **b** of a bronze Roman coin that show two main different areas (A, B) revealing the inhomogeneities of the material



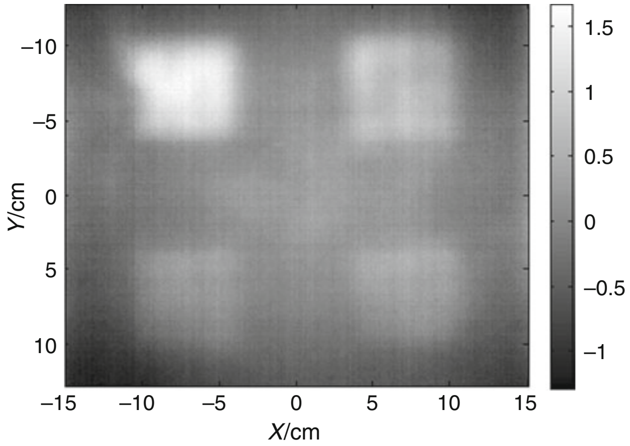


Fig. 11 Raw thermogram of a laboratory sample, recorded 100 s after the end of 90 s long heating produced by two 500 W halogen lamps. Four square mosaic areas are shown by the thermograms, each of them being composed by nine 2 × 2 × 1 cm polystyrene parallelepipeds. The presence of the mosaics is clearly detectable but the spacing between the *tesserae* cannot be observed [29]

structure and for the local characterization (see, for instance [33]). One of the main causes of degradation of frescoes derives from the exposure to unsuitable environmental conditions which can generate thermal, hygrometric and consequently mechanical stress, inducing variations of moisture content of the artefact [34]. In this respect, the various thermographic methods can provide an aid in the investigation of frescoes [10], generally made of a support of marble, brick or tuff and covered with a layer of plaster where the typical defects of fresco decay, like detachments and cracks, are located [35]. Moreover, thermography, while inducing only moderate temperature increase, can point out the fine difference between layers of paint, plaster and concrete, possibly applied at different times because of restoration. Such capability of the IRT has been recently tested in a number of test samples and original artefacts [36–38]. It is worthwhile mentioning the study performed on a reproduction of the Giotto's fresco *Meeting at Golden Gate* made with the same executive techniques and materials of the past and where a number of typical defects of fresco degradation had been purposely created at different depth [36]. In such a case, the analysis has been performed by recording the 2 min long constant heating and the subsequent cooling-down process. In other IRT investigation reported in the literature, the heating can be hours long [37]. In all cases, the heating procedure of the sample represents an aspect that must carefully evaluated for this kind of analysis. The variation of the temperature, ΔT, and of the moisture content (and/or relative humidity RH at the surface) induced in the fresco by the thermal perturbation must be kept below specific threshold values in order to prevent damage. It has been shown, by monitoring, ΔT and RH values during the measurement, that a successful investigation can be safely obtained inducing a slow temperature increase of less than 2 °C and a decrease of RH of less than 10% [37]. Finally, it must be mentioned that such a kind of investigation usually requires the data to be adequately processed in order to improve the infrared signature of the defects and to reduce the impact of non-uniform heating and emissivity difference associated with the various painting pigments.

Paintings on canvas and wood Different thermographic approaches (pulsed thermography, pulsed phase thermography [39], etc.) have been used for the analysis of wood-based and canvas-based paintings, providing successful results, for instance, in the detection of delaminations and degraded regions. Such thermographic methods can be integrated with other techniques which allows, for example, to detect subsurface features like corrections on the paintings performed by overpainting new scenes. In particular, reflectography, a method based on the analysis of the reflected near infrared (NIR) radiation, has allowed the detection of features like underdrawings and sketches [40]. The integrated use of reflectography and thermography, in

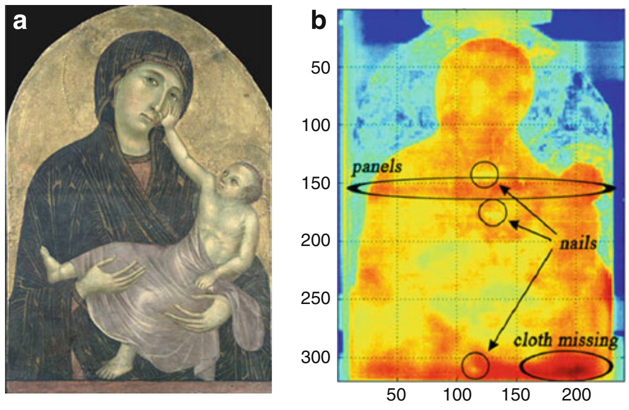


Fig. 12 Photograph **a** of the Cimabue's "Virgin with child", tempera on panel, thirteenth century, Santa Verdiana museum, Castelfiorentino, Italy. Thermogram **b** revealing the three nails inserted into the wooden support and the junction of the panels [42]

particular, can provide a deeper understanding of the painting [39]. NIR reflectographic inspection may allow to go through the various steps associated with the making and the possible successive restoration of the artwork. On the other hand, thanks to thermography, surface and volume defects of the structure, can be pointed out. In the study of paintings on wood, thermography can detect features associated with wood ageing, like hollows and cracks [41]. Ambrosini et al. have recently presented an analysis of the wood painting attributed to Cimabue: the *Virgin with Child* (Santa Verdiana Museum in Castelfiorentino) (Fig. 12a). The analysis was based on the integration of thermographic and reflectographic data in order to map the hidden features and the degradation effects on the artwork. The investigation has been performed by monitoring the increase of the surface temperature during the application of a stepped heating pulse. The painting was heated for 2 min at low power using two tungsten 6 kW lamps, leading to a temperature increase of 1.7 °C. The obtained results showed some iconographical features and structural anomalies (Fig. 12b) like, for example, the presence of three nails inserted into the wooden support and a barely visible horizontal shade corresponding to the junction of the panels [42].

Bronze sculptures

Active thermography has been also applied to the investigation of bronze artworks, like in the case of the analysis performed on the copy of the equestrian statue of Marco Aurelio (Fig. 13), located in Piazza del Campidoglio in Rome [11]. Before the final assembly, parts of the statue were studied by pulse IRT, heating them by means of three 3 kW lamps. In order to maximize the emissivity of the sample, the analysed parts had been previously coated with colloidal graphite (Fig. 13a), later removed by different cleaning treatments (Fig. 13b). In Fig. 13c, the thermogram of the Marco Aurelio's face is reported. It shows, during the cooling phase, the surface temperature variation, reflecting the thickness difference among the various parts of the bronze. Similarly to the case of the Greek ceramic described previously (Fig. 6b), once the thermal diffusivity was measured ($D = 0.19\,\mathrm{cm}^2\,\mathrm{s}^{-1}$), the thermogram could be converted into a calibrated thickness map, providing thickness values ranging from 4.8 mm, in between the nose and the eyes, to 9.2 mm below the nostrils. A qualitative IRT investigation of other parts of the sculptures revealed the presence of voids and allowed the detection and analysis of the inner welding and reinforcements of the structure of the statue.

The promising perspectives of active IRT for the study of the surface modelling in bronzes that have been cast with the lost-wax technique should also be mentioned. The workings, such as the chiseling, the filing and the use of fillers produce plastic deformations and inhomogeneities in the structure of the bronze. The tracks, left by employed tools, are erased following the final polishing of the bronze surface but can be identified by IRT. This provides relevant information on the modus operandi typical of the specific

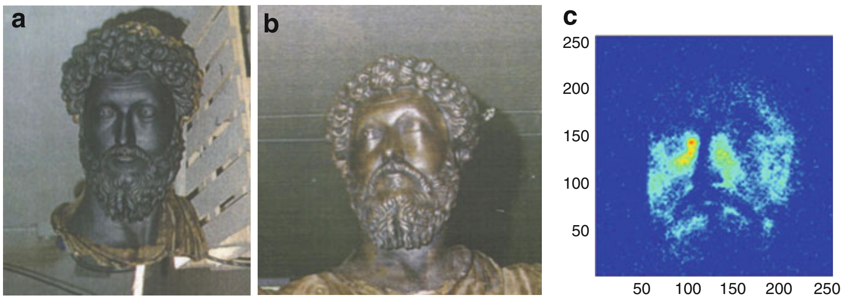


Fig. 13 Bronze copy of the Marco Aurelio statue, now located in Piazza del Campidoglio (Rome). The photographs, taken during the statue making, show the Emperor's head **a** coated with removable colloidal graphite for a better thermographic analysis and **b** after the first stage of removal. The thermogram **c** reveals the thickness variation of the face

artist and on the method of manufacture which refers to a specific artistic tradition.

Conclusions

We have reported on several applications of the active IRT which show that the technique can be successfully applied to the study of a large variety of cultural heritage of different structures and composed by different materials. Due to the specific non-destructive character required for the study of cultural heritage, most of the thermographic investigations performed in this field required the developing of adequate new procedures, characterized by careful heating of the artefact and by the reversible treatment of the sample surface, when required. Often the adopted technical solutions are non-standard and therefore stimulate the development of new configurations and/or the integration of the IRT with other investigation methods, such as the other non-destructive digital imaging techniques widely applied to the cultural heritage investigation. Among them infrared reflectography, X- and γ-rays analysis, ultraviolet fluorescence, multi and hyperspectral analysis, 3D scanning, thomographies of different nature (X and γ rays, neutron, optical coherence, etc.) should be mentioned, all of them providing complementary digital imaging and data that can be easy processed together with the IRT data.

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