



THERMOGRAPHIC ANALYSIS OF CULTURAL HERITAGE: RECENT APPLICATIONS AND PERSPECTIVES

REVIEW

Fulvio Mercuri*, Noemi Orazi, Ugo Zammit, Stefano Paoloni,
Massimo Marinelli, Pier Paolo Valentini

This paper is based on a presentation at the 2nd International Conference "Matter and Materials in/for Cultural Heritage" (MATCONS 2011) in Craiova, Romania, 24-28 August 2011.

Guest editor:
Dr. Elena Badea

Dipartimento di Ingegneria Industriale,
Università di Roma "Tor Vergata", Via del
Politecnico 1, 00133 Rome, Italy

corresponding author:
fulvio.mercuri@uniroma2.it

Infrared thermography (IRT) has shown to be an important non-destructive method for the investigation of cultural heritage. More specifically, active IRT, monitoring the evolution of emitted infrared radiation at the surface of a sample with time, provides information on the structure of the artefact as well as on the thermal properties of the constituting material. The technique has been applied to the study of library objects, archaeological findings and works of art, enabling detection and characterization of different surface and sub-surface features. In this work, we present some recent applications of active IRT to the structural analysis of historical book bindings and of earthenware, to the detection of manuscript texts buried in the structure of books and to the characterization of repairs and cold workings on historical bronzes. In addition, we present the recent development in 3D thermographic imaging of sub-surface features of an artefact by integrating thermography with 3D scanning.

1 Introduction

During the recent decades, different techniques have been used for the inspection of structures and materials in the field of cultural heritage such as X-ray radiography,¹ infrared reflectography, ultraviolet fluorescence, multispectral and hyperspectral imaging.² In particular, different types of cultural heritage objects have been inspected by means of infrared thermography (IRT),³⁻⁵ a technique used for its non-destructive nature and its capability to perform both qualitative inspection of surface and subsurface features and quantitative analysis of thermal transport quantities.

IRT techniques can be divided into two categories, classified as passive and active thermography. The passive methods monitor the infrared (IR) emission associated with the temperature evolution due to the heating and cooling phenomena naturally occurring in the investigated system. The passive approach has been successfully applied, for instance, to the study of buildings and to the *in situ* inspection of structures in important archaeological sites by taking advantage of the temperature variation occurring during a daily thermal cycle.⁶ In particular, thanks to the heat flow induced through building walls, it has been shown that features such as masonry texture under the plaster and hidden architectural elements in general can also be investigated.⁷⁻¹⁰ With passive IRT the analysis of the IR emission distribution allow us to obtain mostly qualitative information.

received: 08.12.2011
accepted: 20.12.2012

key words:
active infrared thermography, bronze
sculpture, parchment binding, 3D imaging

The active approach, on the other hand, allows us to obtain quantitative as well as qualitative information, by monitoring the transient temperature change induced in artefacts by adequate artificial heating, usually induced by the absorption of light emitted by lamps, lasers or other sources.

Recently, active IRT has been used to investigate the preservation state of different library and archive materials to study ageing of parchment and to characterize defects such as micro fractures in its structure.¹¹ Analysis, performed by combining measurements of thermal diffusivity with thermal imaging, provided useful quantitative information to characterize parchment microstructure.¹²

Different thermographic methods have also been applied to the analysis of paintings on canvas and wood, to monitor their thickness and adhesion to the support.¹³ Applications have also been developed for fresco plasters to detect delaminations, cracks, detachments and inclusions. In a study of underdrawings, thermographic results have been integrated with those obtained by other techniques such as reflectography, which is based on the analysis of the reflected near infrared radiation (NIR).¹³ Active IRT can also complement holographic methods revealing deformations related to structural faults.¹⁴

For bronze sculptures, active thermography has been used to measure the difference in thickness in different parts of a sculpture, to evaluate changes in thermal diffusivity, and to detect voids and inner weldings in a bronze structure.¹⁵

In this work, we report on recent applications of the active IRT technique, particularly to library materials, where the detection and characterization of subsurface features was enabled, such as the binding structure, defects, deteriorated areas and inhomogeneities.^{12,16} Additionally, the presence of texts hidden beneath the surface of glued paper sheets, originating from older documents, has been detected in several cases. Other active IRT investigations include those carried out on bronze sculptures, enabling the study of several working steps normally performed after casting by the lost wax method. This includes procedures such as repairs, fillings and surface cold modelling,¹⁷ which are concealed beneath the polished and patinated surface of a sculpture. Active IRT has been shown to be successful in detecting and characterizing specific hidden marks of cold working providing useful information to solve historic and artistic research questions.

Finally, we mention possible future development of IRT applications in the field of cultural heritage, and integration with 3D scanning to obtain a new method for 3D IRT reconstruction of subsurface features.

2 Experimental

Active IRT consists of the analysis of the IR radiation emitted from the surface of a sample which has been stimulated by a thermal perturbation. The detection by an infrared camera provides maps of locally emitted radiation known as thermograms (Fig. 1). These maps are images revealing surface and subsurface structural and compositional features. The heat diffu-

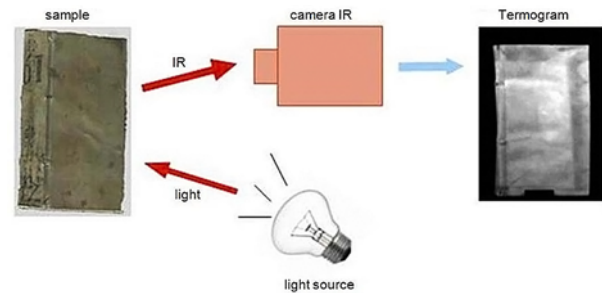


Figure 1: Active IRT experimental set-up. An infrared camera records the IR emission maps of the sample following heating produced by light /radiation absorption.

sion process taking place through the sample volume is uniform in the case of a homogeneous material and gives rise to a homogeneous evolution of the temperature distribution at the sample surface. On the contrary, the presence of inhomogeneities, at/or beneath the surface, affects local heat propagation and results in a non-uniform temperature distribution at the surface.

With a given distribution of detector elements in the focal plane array of the employed camera (320x240 in our CEDIP Jade MWIR), the spatial resolution in the plane of the investigated artefact surface depends on the adopted camera optics and could, in our case, resolve features down to 0.1 mm. As far as the depth resolution is concerned, it depends on thermal transport properties of the material constituting the investigated sample, the subsurface structure, and on the frame rate of the acquisition system. For example, with a frame rate of 1.1 kHz in bronze, the depth resolution was 0.1 mm.

A large number of active IRT configurations and set-ups have been employed in the investigations performed on various cultural heritage objects, the main ones being pulsed IRT and lock-in IRT. Pulsed IRT basically consists of heating a sample for a short-time interval (typically a few ms) and then detecting the evolution of the local surface IR emission with time. The heating is usually induced by means of flash lamps whose power is limited in order to prevent damage to the sample.¹⁸ The temperature increase immediately following a pulse can actually reach a few degrees at most, and is generally rather uniform across the sample area. In the lock-in IRT configuration, 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 local oscillating temperature field are retrieved. The phase image, which is associated with the thermal wave propagation time, is independent of the optical properties of the sample and is not affected by the local difference in the light absorption and the IR emissivity which can both influence the amplitude images.¹⁹

It should be pointed out that the analysis of the IRT signal vs. time (in pulsed IRT) or vs. frequency (in lock-in IRT) allows the detection and the study of subsurface features at different depth.¹ So, besides being able to provide complementary information with respect to most of the other mentioned diagnostic

techniques, this depth profiling capability is a peculiarity that few other techniques can offer.

3 Results and Discussion

In this work, the results of the thermographic analysis obtained on historical books and on a copy of a bronze by Giovanni De Martino are reported. Moreover, a recent 3D development of the active IRT is presented showing the results obtained on a Roman amphora.

3.1 Books

Previously, we applied active IRT to the study of several historical bindings. Information about their structural elements such as the cover and the connection between the binding and the book-block could be obtained without dismantling the book. The preservation state of the component materials could also be analyzed by means of active IRT by detecting damaged areas and by monitoring changes to their physical properties.¹² The results presented in this work show the interlayer between the end paper and the board where a number of bookbinding elements (bands, wings, turn-ins, etc.) are located. Such elements could be detected and their shape and adhe-

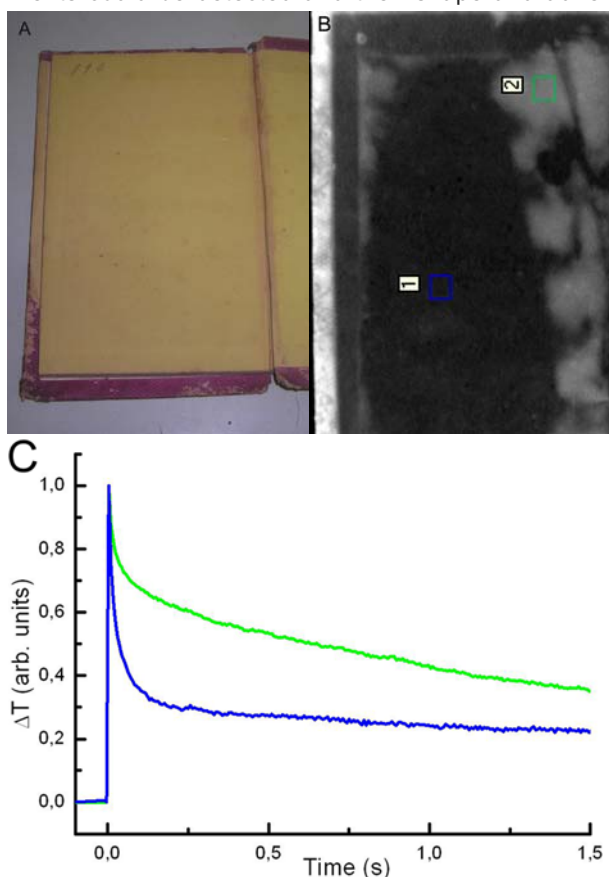


Figure 2: (A) Photograph and (B) thermogram of the end paper, of a 19th-century volume with a rigid board. The darker area corresponds to the part where the contact between the turn-in of the cover and the board and between the end paper and the board is good. (C) The blue and green curves show the temperature change vs. time corresponding to the investigated areas indicated, respectively, by the blue (1) and green (2) squares in Fig. 2B.

sion state characterized. In Figure 2 the photograph (2A) and the thermogram (2B) of a 19th century volume supported by a rigid board are shown. The dark areas in the thermogram correspond to those where, thanks to the good contact between the turn-in of the cover and the board, the heat diffusion is more efficient and the surface cools down more rapidly. The large central dark area corresponds to that of good adhesion between the end paper and the board. The light area on the right hand side reveals a detachment of the end paper crossed by three darker stripes corresponding to the positions of the bands.

The different quality of adhesion of the end paper to the underlying board is well indicated also by the two curves in Figure 2C, showing the corresponding temperature change vs. time. The peak position of the two temperature curves coincides with the instant of the flash activation and the consequent end paper heating. The blue curve shows a cooling process in the central area of the board which is more rapid than that described by the green curve, corresponding to the temperature decay in the area close to the inner joint. In the latter, the lack of adhesion between the end paper and the board acts as a thermal barrier for heat diffusion in the subsurface volume of the artefact, thus making the cooling process less efficient.

The image in Fig. 3A shows the back end paper of an 18th-century volume with a hardback parchment cover. The corresponding thermogram (Fig. 3B) reveals the structural elements at the rear side of the cover, beneath the end paper. In particular, the bands (indicated by the arrows) kept in contact with the board by a glued paper wing (framed by the red rectangle) are detected. The lighter area on the right hand side of the thermogram reveals a detachment of the turn-in from the board.

In addition to structural analysis, active IRT has enabled identification of texts hidden beneath the end papers and other glued elements. The thermogram in Fig. 4B, obtained by illuminating the end paper by means of two 3-kW flash lamps at 45° with respect to the leaf, refers to the volume with the parchment hardback cover in Fig. 4A. It shows different texts on paper strips that were cut off from earlier manuscripts and used to support the binding between the cover and the spine. The capability of the IRT to analyse bookbindings without dismantling the books repre-

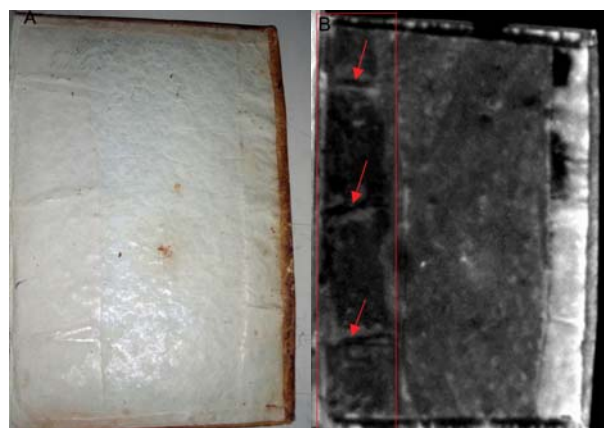


Figure 3: (A) Photograph and (B) thermogram of an 18th-century volume with a parchment hardback cover. The arrows indicate the bands in contact with the board.

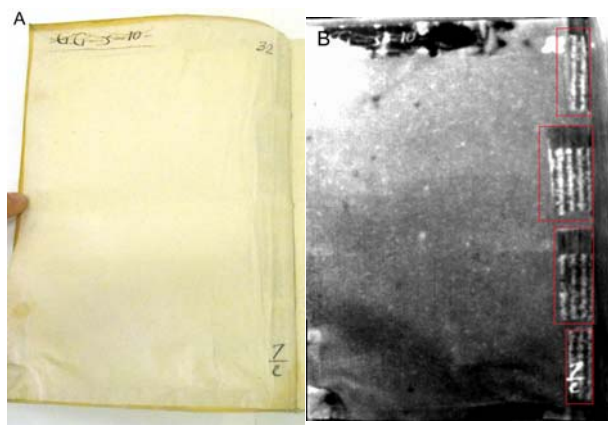


Figure 4: (A) Photograph and (B) thermogram of a volume with parchment hardback cover. The red rectangles mark the hidden writings on paper strips of an earlier manuscript used for the binding beneath the spine.

sents a powerful tool both for their study and conservation.

In Fig. 4B the thermal contrast is due to the light selectively absorbed by the ink buried beneath the paper leaf, contrast which could also depend on the type of ink employed (i.e. iron gall, carbon black etc).

3.2 Bronzes

Another application of active IRT is concerned with surface re-modelling of bronze artefacts that have been cast by the lost-wax technique. In this work we report on an investigation performed on a copyⁱ of an original bronze by Giovanni De Martino obtained using the indirect casting method. Some typical defects, repairs and cold working marks, related to the casting of bronze statues, have been reproduced on the copy and analyzed by means of active IRT, to test its capability to detect such features.¹⁷

Voids are one of the possible defects and are usually repaired by inserting metal plugs into the bronze or by using the filling procedure. Whenever possible, plugs were made from the material removed from the casting sprues. Small defects and surface pores were mostly filled with wax resin filler mixed with the cast bronze powder. In the present case study¹⁷ such a mixture was used to fill small voids located in the area of the forehead shown in Fig. 5A. After the repairs were carried out, the surface was smoothed by means of files and chisels and, finally, patinated. In Fig. 6A the red rectangle marks the area shown in the thermogram of Fig. 6B where a plug is clearly detectable and indicated by the arrow. Since the material of the plug was the same as that of the artefact, the contrast between the plug and the surrounding areas was ascribed to its larger thickness. In fact, with respect to the surroundings, the area of the thicker plug is characterized by heat diffusing for a longer period of time before reaching the opposite end of the bronze, thus leading to more efficient cooling and consequently appearing darker in the thermogram. The so called cold workings performed on the bronze surface after the casting can be revealed by qualitative thermographic imaging analysis. In selected areas, a correlated quantitative study of

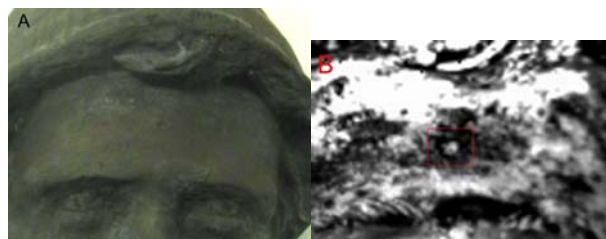


Figure 5: (A) Photograph and (B) thermogram of a small filling framed by the circled area.

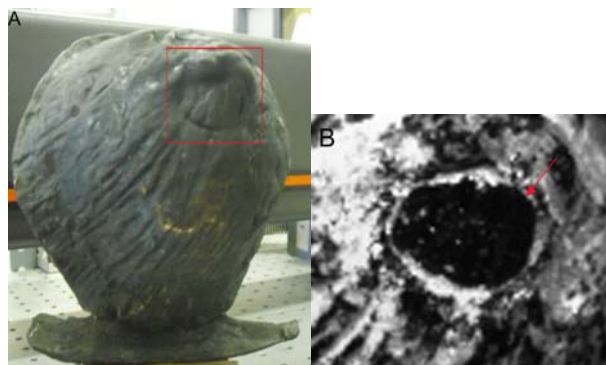


Figure 6: (A) Photograph and (B) thermogram of the bronze plug located on the hat. The arrow indicates the bronze plug.

properties such as thermal diffusivity can be performed, the value of which depends on material structure. We have already reported^{11,12} that the thermal diffusivity can be used to monitor the ageing process in parchment samples. We have tested the effects of particular cold working steps on the value of thermal diffusivity on some bronze test samples, by performing the analysis before and after the cold working and also following a subsequent furnace treatment. The variations in the thermal diffusivity values were then correlated to those of parameters which are related to the structural state of the material such as, for example, hardness, XRD peak position and its width. We found that the thermal diffusivity value $D = 0.18 \pm 0.02 \text{ cm}^2 \cdot \text{s}^{-1}$, measured along the sample surface for the *as cast* bronze, showed a decrease of about 20% after the chiselling process, due to the defects building up in the sample volume hindering natural heat diffusion in the material. The thermal diffusivity was restored to approximately its original value following the annealing of the defects induced by the thermal treatment at 700 °C for 20 min. Both the hardness and the XRD peak width also behaved according to the above-mentioned defect scenario. In fact, for instance, in the chiselled area the hardness increases by about a factor 2, the XRD width increases by about 40%, while the XRD position showed no significant change. They all tended back approximately to their original value following the heat treatment.²⁰

3.3 3D Thermography

The application of active IRT to investigation of cultural heritage stimulated its integration with methods such as other non-destructive digital imaging techniques. We tested different types of artefacts using a new system for 3D thermography based on the inte-

ⁱ The bronze copy has been made by Augusto Giuffredi and Carlo Stefano Salerno. An extensive report of this study is in preparation.

gration of 3D laser scanning procedures with active IRT. The case of the neck of a Roman terracotta, previously studied by active IRT, is presented here.⁵ Its surface has been analyzed to characterize the nature of the concretions and, among them, tracks left by various molluscs. For example, the adhesion between two different shells and the earthenware was assessed and the presence of inter-layers beneath the shells revealed (circled areas in the thermogram, Fig. 7A). Fig. 7B reports the temperature change vs. time recorded in the blue and green circled areas in Fig. 7A. The interlayer in the blue area, because of the faster decay of temperature shown by the blue curve with respect to the green one, denotes a better thermal contact of the shell with the substrate, while, presumably, a detachment of the underlying concretion occurred in the green area. This explanation is also supported by the features shown in the thermogram in Fig. 7A where the green area appears hotter than the blue one.

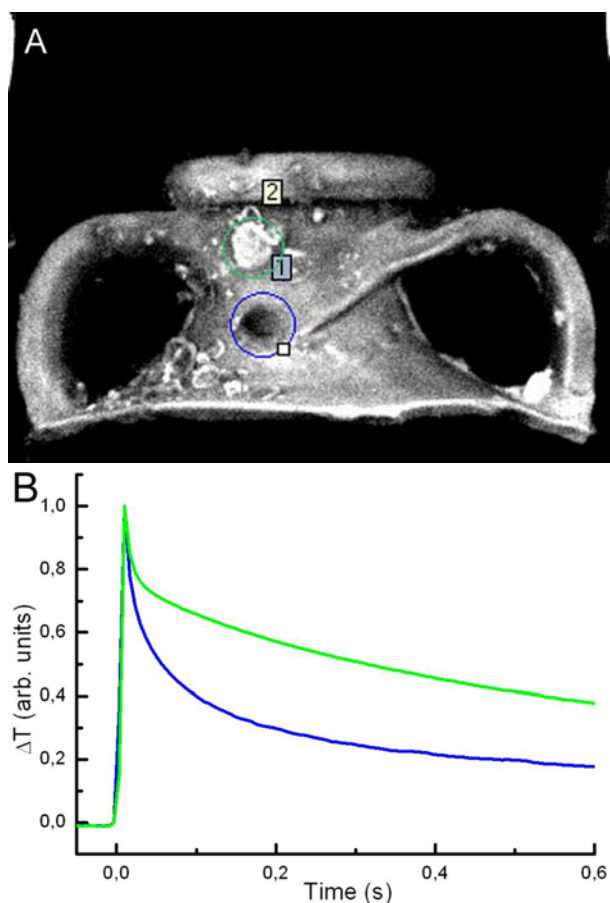


Figure 7: (A) Thermogram of the neck of a Roman amphora. The circled areas show different interlayers between two shells and the earthenware. (B) The curves of the temperature change vs. time recorded in area 1 (blue) and 2 (green).

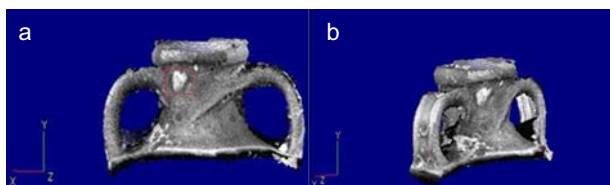


Figure 8: 3D thermographic image of a side view (A) and of an oblique view (B) of the neck of a Roman amphora.

By integrating the thermographic results with 3D scanning, a 3D thermographic reconstruction of the terracotta was obtained (Fig. 8), where surface and sub-surface features appear in their position on a 3D geometrical reconstruction which can be freely reoriented to provide the most suitable point of view.

4 Conclusion

We have illustrated some of the recent applications of the active IRT technique to the study of historical books, bronze and terracotta artefacts. The analysis is performed non-destructively, which is a fundamental requirement for such applications. In particular, two historical books have been investigated in order to study, without dismantling them, their structural elements and the connection between the binding and the book-block. Active IRT has also enabled the identification of texts buried beneath the end papers and other glued sheets, cut from earlier manuscripts and used to reinforce the bookbinding. A copy of an original De Martino's bronze was also studied, where some typical defects, repairs and cold workings, which normally follow the casting, had been applied on purpose. The surface of a Roman amphora neck has been analyzed to characterize the nature of concretions, traces left by various molluscs and adhesion between shells and the earthenware.

The capabilities of the IRT analysis can be greatly enhanced by integrating it with other techniques, such as X- and γ -ray analysis, Energy Dispersion Spectroscopy (EDS), X-Ray Diffraction (XRD), X-Ray Fluorescence (XRF), or 3D laser scanning. In particular, we have presented a new integration of the IRT with 3D laser scanning, providing a 3D thermographic reconstruction of an artefact for better visualisation of surface and subsurface features.

5 Acknowledgements

The authors would like to thank Roberto Volterri, Dipartimento di Ingegneria Industriale, Università di Roma "Tor Vergata", for providing library and archaeological materials and Cristina Cicero from the same Department, for the helpful comments and suggestions. They also wish to thank Augusto Giuffredi, Accademia di Belle Arti di Milano, and Carlo Stefano Salerno, ISCR- Istituto Superiore per la Conservazione e il Restauro di Roma, for providing the bronze copy and for their contribution in the analysis of bronze material.

6 References

1. X. P. V. Maldague, *Theory and practice of infrared technology for non destructive testing*, in: K. Chang (ed.), Wiley Series in Microwave and Optical Engineering, John Wiley & Sons, New York, USA, 2001.
2. C. Fischer, I. Kakoulli, *Multispectral and hyperspectral imaging technologies in conservation: current research and potential applications*, Stud. Conserv., Supplement 1, 2006, **14**, 3-16.
3. T. Sakagami, S. Kubo, *Applications of pulse heating thermography and lock-in thermography to quantitative nondestructive evaluations*, Infrared Phys. Technol., 2002, **43**, 211-218.

4. N. Rajic, *Principal component thermography for flaw depth characterisation in composite structures*, Compos. Struct., 2002, **58**, 521-528.
5. F. Mercuri, U. Zammit, N. Orazi, S. Paoloni, M. Marinelli, F. Scudieri, *Active infrared thermography applied to the investigation of art and historic artifacts*, J. Therm. Anal. Calorim., 2011, **104**, 475-485.
6. G. M. Carlomagno, R. Di Maio, M. Fedi, C. Meola, *Integration of infrared thermography and high-frequency electromagnetic methods in archaeological surveys*, J. Geophys. Eng., 2011, **8**, S93.
7. N. P. Avdelidis, A. Moropoulou, *Applications of infrared thermography for the investigation of historic structures*, J. Cult. Heritage, 2004, **5**, 119-127.
8. A. Moropoulou, N. P. Avdelidis, M. Kouli, E. Delegou, T. Tsiourva, *Infrared thermographic assessment of materials and techniques for the protection of cultural heritage*. Proceedings of SPIE 4548, Multispectral and Hyperspectral Image Acquisition and Processing, China, 25 September 2001.
9. E. Grinzato, G. Cadelano, P. Bison, P. Petracca, *Seismic risk evaluation aided by IR thermography*, Proceedings of SPIE 7299, Thermosense XXXI, Orlando, 22 April 2009.
10. E. Grinzato, P. G. Bison, S. Marinetti, *Monitoring of ancient buildings by the thermal method*, J. Cult. Heritage, 2002, **3**, 21-29.
11. G. Colombo, F. Mercuri, F. Scudieri, U. Zammit, M. Marinelli, R. Volterri, *Thermographic analysis of parchment bindings*, Restaurator, 2005, **26**, 92-104.
12. A. Riccardi, F. Mercuri, S. Paoloni, U. Zammit, M. Marinelli, F. Scudieri, *Parchment Ageing Study: New Methods Based on Thermal Transport and Shrinkage Analysis*, e-Preserv. Sci., 2010, **7**, 87-95.
13. D. Ambrosini, C. Daffarra, R. Di Biase, D. Parlotti, L. Pezzati, R. Bellocci, F. Bettini, *Integrated reflectography and thermography for wooden paintings diagnostics*, J. Cult. Her., 2010, **11**, 196-204.
14. V. Tornari, *Optical and digital holographic interferometry applied in art conservation structural diagnosis*, e-Preserv. Sci., 2006, **3**, 51-57.
15. F. Scudieri, F. Mercuri, R. Volterri, *Non-invasive analysis of artistic heritage and archeological findings by time resolved IR thermography*, J. Therm. Anal. Calorim., 2001, **66**, 307-314.
16. M. Marinelli, F. Mercuri, F. Scudieri, U. Zammit, G. Colombo, *Thermographic study of microstructural defects in deteriorated parchment sheets*, J. Phys. IV, 2005, **125**, 527-529.
17. N. Orazi, F. Mercuri, S. Paoloni, U. Zammit, M. Marinelli, F. Scudieri, C. S. Salerno, A. Giuffredi, *Thermographic inspection of historical bronze statues*, Proceedings of art'11, Florence, 13-15 April 2011.
18. X. P. V. Maldague, F. Galmiche, A. Ziadi, *Advances in pulsed phase thermography*, Infrared Phys Technol., 2002, **43**, 211-218.
19. X. P. V. Maldague, *Theory and Practice of Infrared Technology for Non Destructive Testing*, in: K. Chang (ed.), Wiley Series in Microwave and Optical Engineering, John Wiley and Sons, New York, 2001.
20. G. Costanza, private communication.