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Non destructive testing of works of art by stimulated infrared thermography

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Abstract

In this work, we present various examples of assistance to the restoration of works of art by stimulated infrared thermography. We show initially that the method allows the detection of delamination located in mural paintings, such as in the «Saint Christophe» of the Campana collection of the Louvre French museum. We show then that it also makes it possible to detect delaminations or galleries of worms in marquetry. We show in a third stage that it provides for the detection of detachment of greyness in stained glasses. We show in a fourth stage that it allows the visualization of shards or metal insert located in a Greek “panathénaïque” amphora of the French National museum of the Ceramics of Sevres. We show finally, that the method permits the detection of a crack located in an ovoid vase of the same National museum of the Ceramics of Sevres.

Keywords

Work of art, infrared thermography, non destructive testing, photothermal radiometry, mural painting, marquetry, stained glasses, ceramics

1. Introduction

In the area of assistance to the restoration of works of art, the Research Laboratory of Historical Monuments (LRMH), the Research Restoration Centre of the Museums of France (C2RMF) and the art restorers use many physical and chemical instruments. For example, we can cite visible photography, ultra-violet photography, infra-red photography (implemented in natural light, polarized light or in oblique light), X radiography, electron scanning microscopy, spectroscopy, chromatography in liquid or vapour phase, the particle accelerator AGLAE, acoustic sounding, etc. These various methods are very powerful in their areas of application, but are not universal. In addition, certain methods can be difficult to implement, such as the detection of defects in extend mural paintings by acoustic analysis.

New non destructive methods can thus still find their place in the field of the assistance to the restoration of works of art.

One method of non destructive testing is stimulated infrared thermography. The principle of this analysis method is relatively simple. It consists first in thermally exciting the sample to be analyzed, with a luminous flow. The absorption of this thermal stimulus produces a local rise of temperature near the point of excitation. The principle of stimulated infrared thermography consists then of observe the photothermal signal emitted by the sample using an infrared camera. The resulting photothermal signal depends on the optical and thermophysical properties of analyzed sample, allowing for it to be characterized. This method allows for the thermophysical analysis of thin materials both non destructively and without contact. It has already been implemented to detect and characterize various types of localised or extended defects (delaminations, cracks, inclusions, etc), in various types of materials (metal, composite, etc) [1-8]. Due to this description, stimulated infrared thermography is very fitting for use in the field of the restoration of works of art and for several years now, many teams have used it in this way [9-11].

In this work, five examples of assistance to the restoration of works of art by stimulated infra-red thermography are presented including:

- 1) The detection of delaminations located in mural paintings, such as for example in the «Saint Christophe» of the Campana collection of the Louvre French museum.
- 2) The detection of delaminations or galleries of worms in marquetrys.
- 3) The detection of the detachment of greyness in stained glasses.
- 4) The visualization of shards or metal insert located in a Greek “panathénaïque” amphora of the French National museum of the Ceramics of Sevres.
- 5) The detection of a crack located in an ovoid vase of the same National museum of the Ceramics of Sevres.

2. Experimental set up

2.1. Description of the experimental set up

The experimental systems that we implemented for this study are all based on the same principle. It is the principle of the System of Analysis of Thin Materials by Infra-red Thermography (SAMMTHIR) of the GRESPI laboratory of the Reims University. The excitation optical device is composed of a couple of halogen lamps. Halogen lamps were selected not only because they are inexpensive, but also they lead to only a moderate of the sample's surface temperature. The detection instrumentation is composed of an infra-red camera of thermography. For our study, we have chosen an A20 FLIR Systems™ infra-red camera, because of the good price / performance of this device. Finally, the experimental system implemented for this study used electronic control and data processing software to allow photothermal analysis (figures 1 and 2).



Figure 1: Example of experimental devices used at the laboratory

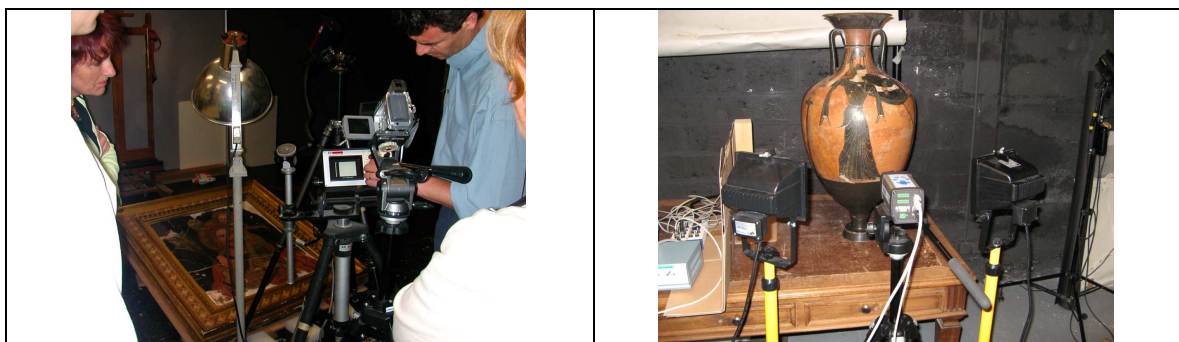


Figure 2: Example of experimental devices used *in situ*

2.2. The excitation signals used

In this study we have used two main type of excitation: pulse excitation and random excitation. The pulse excitation consists in exciting the analysed sample for a given time. The

duration of the pulse depends on the thermophysical properties of the analysed sample. In our case, the works of art studied are insulating materials. Typically the duration of the pulse excitation is from a few seconds to a few tens of seconds. This type of excitation is easy to implement and explains why it is often the first excitation type used in infrared non destructive testing, and why it is the most used in this study.

This kind of excitation leads to an increase of temperature as well which can be relatively important, and a disadvantage for works of art. To avoid this, the random excitation mode may be used.

The principle of random photothermal thermography consists in exciting the material under study by means of a signal approaching white noise, then to reconstruct the pulse response and the harmonic response of the sample by a parametric analysis of the photothermal response obtained.

The parametric analysis is performed by reconstructing the pulse and harmonic responses of the studied physical system from a behavior model, usually of the type ARMA: The ARMA model is built from the analysis of the photothermal response of the sample studied in front of an excitation being the whitest possible (Figure 3)

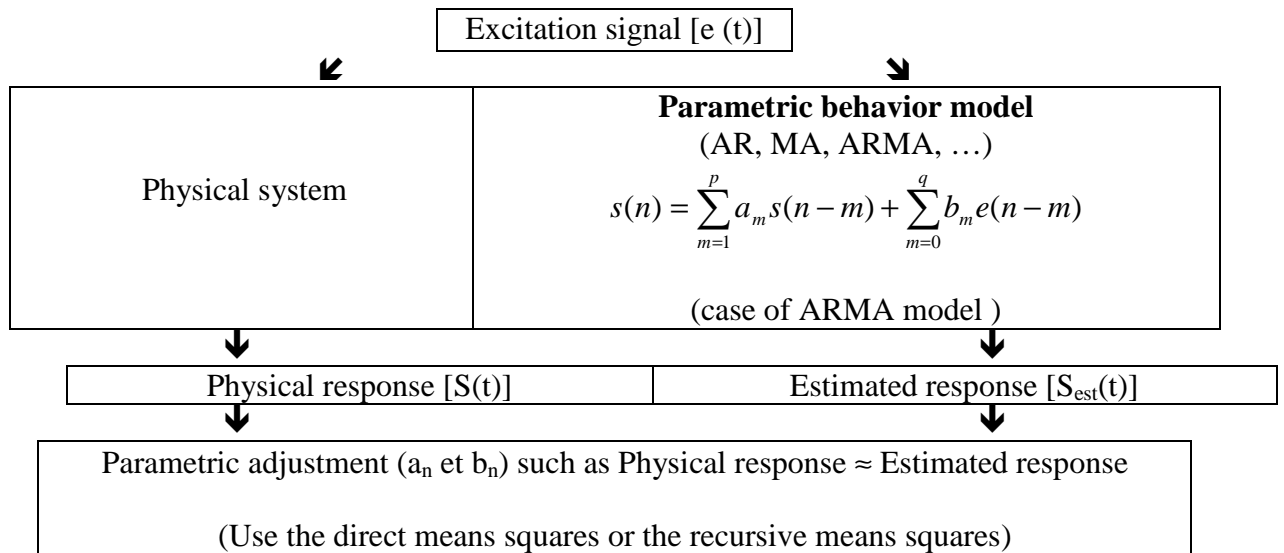


Figure 3: Principle of construction of a behavior model by parametric analysis

The construction of the pulse response is made by calculating the response of the behavior model in front of a Dirac function. The construction of the harmonic response is made by calculating the Fourier transform of this pulse response (Figure 4).

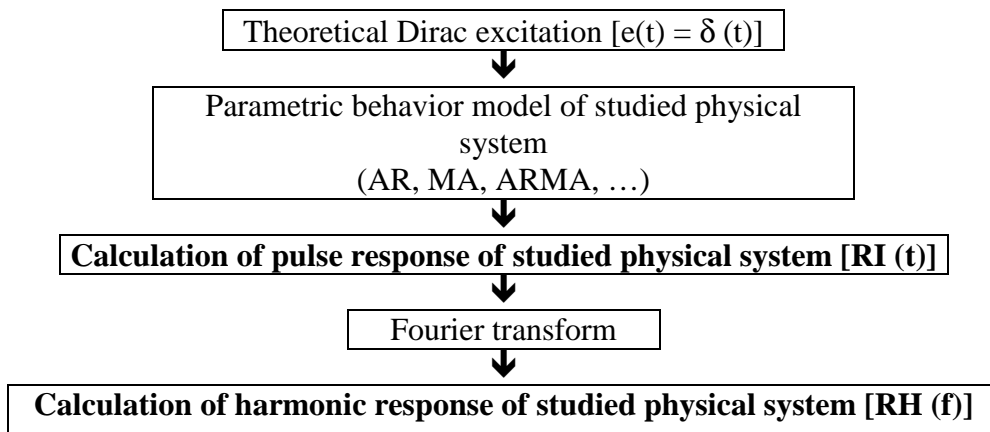


Figure 4: Principle of parametric identification of physical system

Finally, we used the procedures proposed by J.Auvray [12] to build the white noise necessary for these modes of analyses and to build the finest behavior model. He suggests three different manners of approaching this theoretical signal: either build a pseudo random binary sequence, build a Gaussian signal or build a signal with frequency scanning.

In our studies, we implemented the pseudo random binary sequences, essentially for ease of implementation. In this case, the mode of construction of the pseudo random binary sequences consists of collecting the signal delivered at the exit of a register composed of a D flip flop, locked upon itself via a modulo 2 addition (Figure 5). The exits of the D flip flop taken into account during this addition were defined by the primitive polynomials associated with the procedure of creation (Figure 6). An example of a pseudo random binary signal is presented in Figure 7.

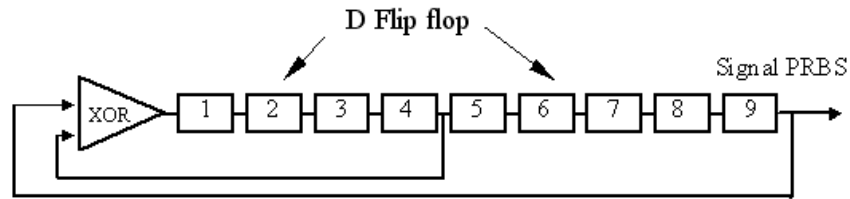


Figure 5: Principle of creation of pseudo random binary sequence

degrees	Primitives polynomials
2	$X^2 + X + 1$
3	$X^3 + X^2 + 1$
4	$X^4 + X + 1$
5	$X^5 + X^2 + 1$
6	$X^6 + X + 1$
7	$X^7 + X^3 + 1$
8	$X^8 + X^4 + X^3 + X^2 + 1$
9	$X^9 + X^4 + 1$
10	$X^{10} + X^3 + 1$

Figure 6: Table of primitive polynomials used to generate pseudo random binary sequence

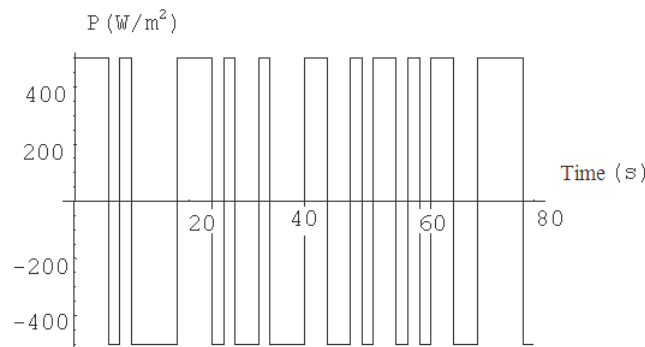


Figure 7: Example of excitation signal usable for the analysis: a pseudo random binary signal

Many potential applications exist for random photothermal thermography due to its main advantages of allowing non-destructive analyses, having lesser energy constraints and giving access to three types of photothermal signals: the raw random response (analyzable by direct deconvolution), the pulse response and the harmonic response of the analyzed material (analyzable by the analysis tools developed for flash and harmonic analyses). Because of

these characteristics, the method is well adapted to non-destructive study of fragile samples such as works of art and is therefore implanted in this study.

In this study, because of the thermal properties of the work of art, we use a frequency excitation of some tenths of seconds. A length of excitation of 256 terms gives a good compromise between the duration of excitation and the smoothness of measurement results. An ARMA model with 40 input and output parameter offers a good reconstruction of the pulse response.

3. Analyses of mural paintings

3.1. Analysis of an academic fresco

The first type of mural painting we analyzed is a partial copy of the «Saint Christophe» of the Campana collection of the Louvre French museum (figure 8 left). The fresco was made according to the primitive Italian technique, from a mixture of lime and plaster. The whole is covered with a pictorial layer, representing the Infant Jesus here. This fresco contains four defects (figure 8 right) of inclusions of plastazote. This fresco was initially made as a martyred sample of the «Saint Christophe» study.



Figure 8: The studied academic fresco (on the left) and the position of the four internal defects (on the right)

In order to detect these defects, we analyzed this fresco by stimulated infrared thermography. The experimental conditions used for this analysis follow. We used a pseudo random binary sequence of excitation, having a length equal to 256 terms and excitation frequency equal to 0.1 Hz. The excitation power was set to 500 W. The detection procedure uses a parametric analysis of ARMA type. Lastly, the number of input and output parameters of the parametric model was 40.

Figure 9 shows the obtained infrared images, in coding false colours (on the left) and a three-dimensional view (on the right). They clearly reveal a more important infra-red signature in the regions of the defects. We can see the appearance of four blue rectangles in the first case and of four bumps in the second case. These characteristic signatures are due to the more insulating thermal properties of the plastazote compared to the lime mixture plasters. Indeed our procedure consists of exciting the sample with visible light. The irradiation of this light slightly heats the surface of the work of art, which is then propagated by conduction in the fresco. The locations of defects are primarily made up of air and are thus more thermally insulating than the lime mixture/plaster on which was deposited the pictorial layer. Therefore thermal propagation is slowed down meaning slower cooling of the surface at the locations of defects and, thus, is noticeable infra-red signature to this place.

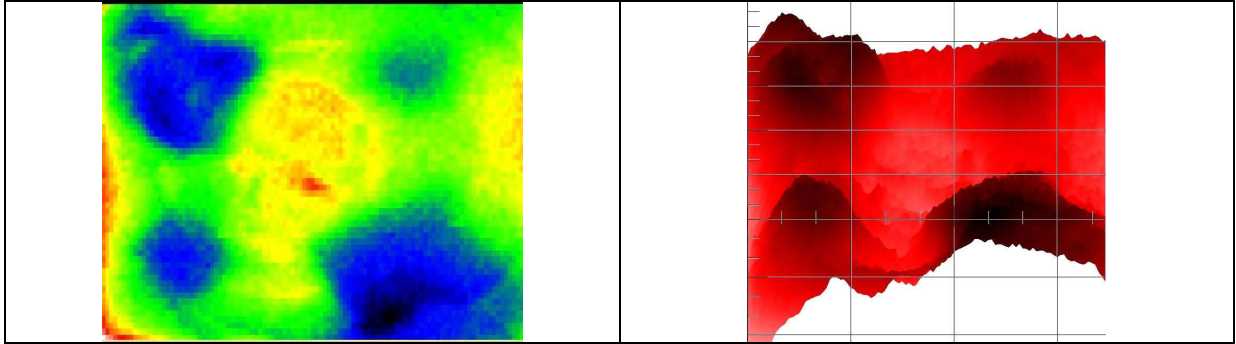


Figure 9: Infra-red photothermal image coded in “false colours” (on the left) and in three-dimensional view (on the right) of the studied academic fresco

3.2. Analysis of the «Saint Christophe»

With the encouraging results obtained on the academic fresco, we analyzed the original fresco of «Saint Christophe» itself. This work of art represents «Saint Christophe» carrying the Infant Jesus and it attributed to Tommaso del Mazza. It was created between 1385 and 1390 and now belongs to the Campana collection of the Louvre French Museum (figure 10).



Figure 10: The studied fresco of the «Saint Christophe»

This fresco was first initially analyzed by an acoustic method by Gabriella Szatanick, art restorer of the inheritance. We then analyzed it, using stimulated infrared thermography in a zone by zone fashion to obtain a sufficient optical resolution for each image. The experimental conditions were the following: a pulsed excitation of 360 s, a power equal to $2 * 800$ W and continuous detection.

An example of a result obtained is presented in figure 11, showing the analysis of the zone close to the right hand of the «Saint Christophe». This figure reveals a dark spot on the level of the right hand of the «Saint Christophe», which is characteristic of the presence of a defect.



Figure 11: Detection of a delamination by stimulated infrared thermography near the right hand of the «Saint Christophe»

In order to validate the results obtained on the whole of the fresco using the photothermal method, we compared them in figure 12 with those obtained by acoustic analysis. This figure shows that the characteristic signatures of visible defects by photothermal radiometry (blue areas, figure 12 on the left) correspond to areas of detachment detected with the acoustic method (grey areas, figure 12 on the right).

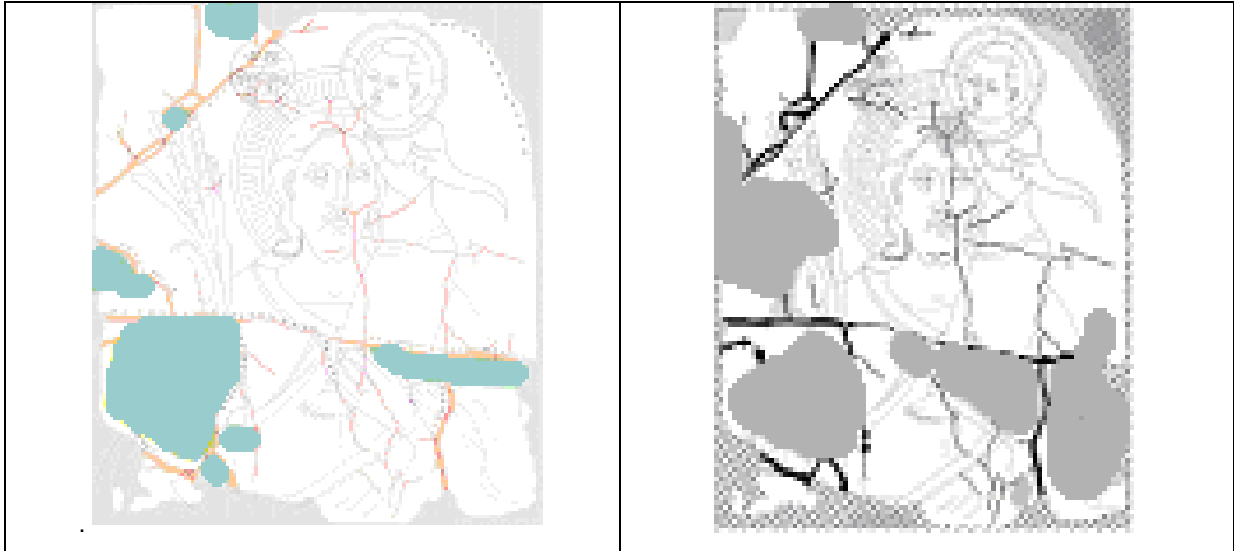


Figure 12: Comparison between experimental results obtained using photothermal analysis (on the left) and acoustic analysis (on the right) of the «Saint Christophe»

4. Analysis of marquetry

The results obtained during the analysis of mural paintings were very encouraging. In a second stage, we investigated the possibilities of using stimulated infrared thermography as assistance with the restoration of marquetry. For this type of work of art we try to find defects of layer separation of marquetry or galleries of worms, which are likely to have photothermal behaviour similar to that of the defects met in the murals paintings, due to their physical nature.

4.1. Analysis of an academic chess-board

The first sample of marquetry we analyzed was an academic chess-board (figure 8 on the left). It includes defects of various sizes to represent separation of marquetry and galleries of worms (figure 13 on the right).



Figure 13: The analyzed academic chess-board (on the left) and the location of the defects (on the right)

The experimental conditions used for the study were a pulsed excitation with duration equal to 31 s. The excitation power was equal to 1000 W. Detection was performed continuously for 512 s.

The photothermal analysis on this chess-board clearly reveals, all of the defects found in marquetry, as shown in figure 14 (left, in false colours view and right in 3D view). As in the previous case, this detection is due to the thermal barrier effect induced by the air filling the defects.

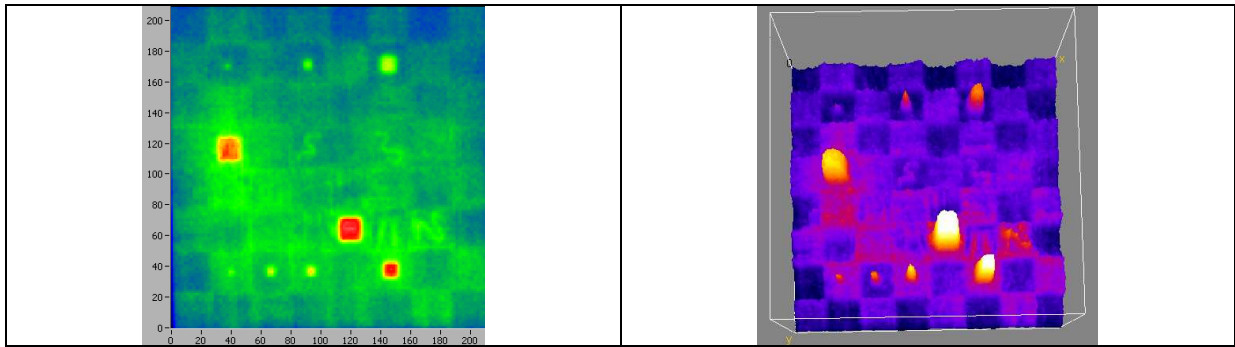


Figure 14: Infra-red photothermal image coded “false colours” (on the left) and three-dimensional (on the right) of the analyzed academic chess-board

4.2. Analysis of samples of the European program “Laseract”

The second type of samples of marquetry we analyzed, were samples provided by the Research Laboratory of Historical Monuments (LRMH) to the European program « laseract » (figure 15). These samples present three types of defects: separations of marquetry (red areas), cracks (green thin lines) and galleries of worms (pointed by arrows).



Figure 15: Four studied samples of marquetry of the program laseract

The experimental conditions for the photothermal evaluation of these samples were: a pulsed excitation with duration of 30 s, an excitation power equal to 1000 W and continuous detection for 300s.

The results obtained are presented in figure 16. Under the conditions of macroscopic analysis implemented, the results show that the method is sensitive to the defects of more significant size like delaminations. They also show that the photothermal signal obtained is sensitive to the drawing present on the marquetry, which is penalizing.

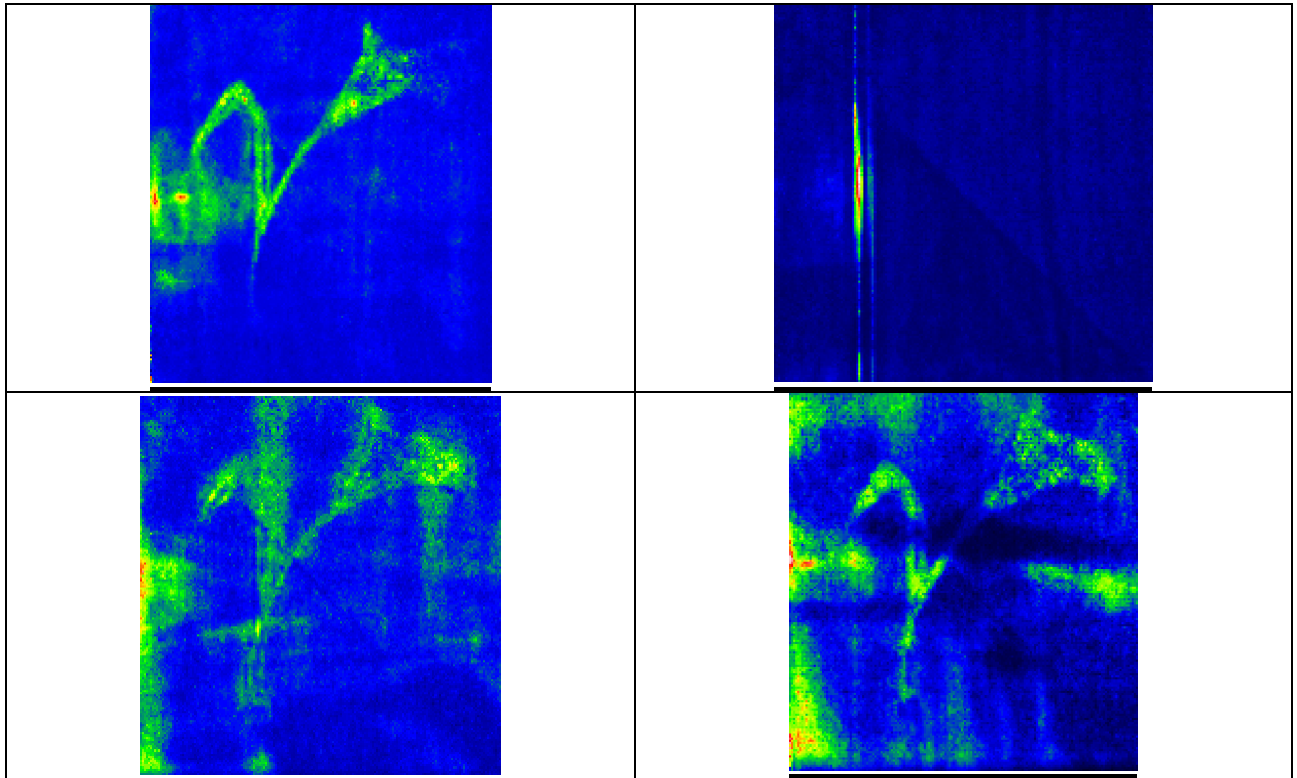


Figure 16: Photothermal results obtained during the study of four Samples of marquetry of the European program laseract

5. Analysis of stained glasses

The third type of works of art we analyzed was stained glass. Stained glass is composed of lead oxide (greyness) deposited on a substrate of glass. This type of coating can also separate from the surface and give defects which from photothermal point of view, are close, to those found in mural paintings and marquetry.

The stained glass analyzed here is a piece from the French Cathedral of “Chartres” presented in figure 17 (on the left). It is covered in the center region with a lead oxide band (greyness). An inspection carried out in reflected light by the Research laboratory of the Historical Monuments revealed a separation of the greyness in the upper part of this oxide band (figure 17 on the right).



Figure 17: The piece of stained glass of the French Cathedral of “Chartres” analyzed (on the left) and the position of the defect detected by the Research laboratory on the Historical monuments (on the right)

The photothermal analysis on this sample was carried out using two methods of excitation. We initially studied it by photothermal radiometry and thus implemented an optical excitation. The second time, we used a flow of hot air, as a different source of excitation, in order to avoid optical problems arising from the first method of analysis.

For the photothermal analysis, the experimental conditions were the use of a pulsed excitation, with duration of 1 s and an excitation power equal to 100 W. Continuous detection was employed with duration of 64 s.

For the excitation with a hot air flux, the experimental conditions were again a pulsed excitation with duration equal to 10 s and an excitation power equal to 1000 W. The detection was made continuously with duration of 60 s.

The obtained results are presented in figure 18, the left for the optical excitation and the right for the hot air flow. They both reveal a noticeable photothermal signal, significant of a separation of greyness, at the place of the defect detected in reflected light by the LRMH. This result confirms this analysis. Additionally, they both reveal other peaks of photothermal signals, perhaps indicating, the presence of other defects.

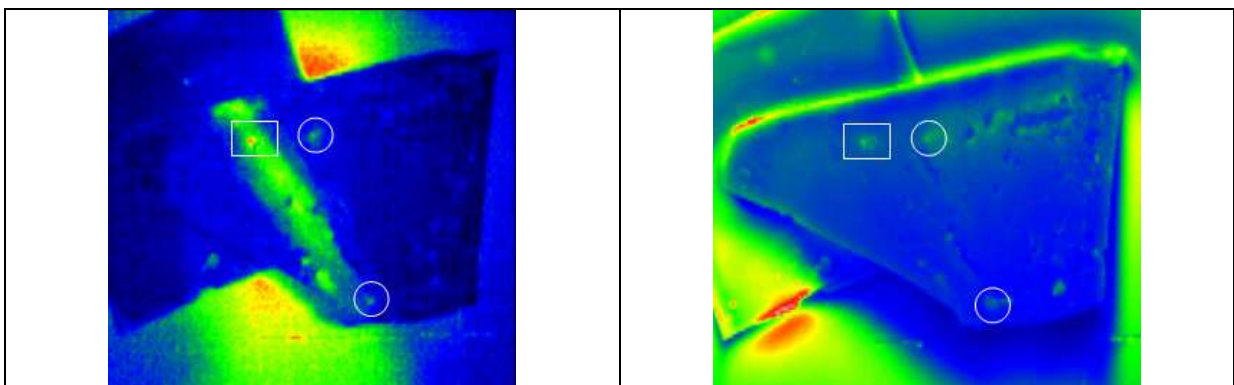


Figure 18: Infra-red photothermal images coded “false colours” obtained under luminous excitation (on the left) and hot air flow (on the right) of the studied piece of stained glass of the French Cathedral of “Chartres “

6. Analysis ceramics

The last types of works of art which we analyzed were ceramics of the French National museum of the Ceramics of Sevres.

6.1. Analysis of a Greek “panathénaïque” amphora (MNC 7230, dated 332 B.C.) of the French National museum of the Ceramics of Sevres

The first ceramics sample analyzed is a Greek “panathénaïque” amphora dated from 32 before Jesus Christ (figure 19). This amphora has been restored on several occasions. It is thus made up of shards assembled using adhesive and metal staple. The first objective of this study was to test the effectiveness of the photothermal method to detect these shards. As the adhesive and staples located between the various shards are of different thermophysical natures than the shards themselves, they behave like defects and thus would seem to be detectable by photothermal thermography.

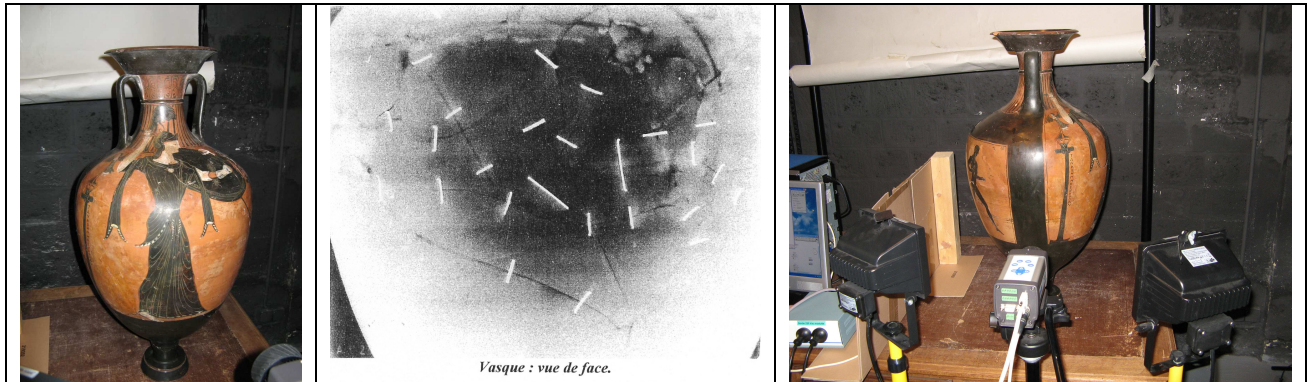


Figure 19: The studied panathénaïque amphora (on the left), its internal structure (in the centre, X radiography) and the face studied by photothermal radiometry (on the right)

The experimental conditions for the study were a pulsed excitation having duration of 120s and an excitation power equal to 1000 W. Detection was continuous and performed for 900 s.

The photothermal results obtained are presented in figure 20. It shows in the left image that the photothermal result is very sensitive to the pictorial layer present on the amphora. The right image shows that the photothermal answer is also sensitive to the thermophysical variations of properties between the adhesive and the shards, which then makes it possible to detect these shards

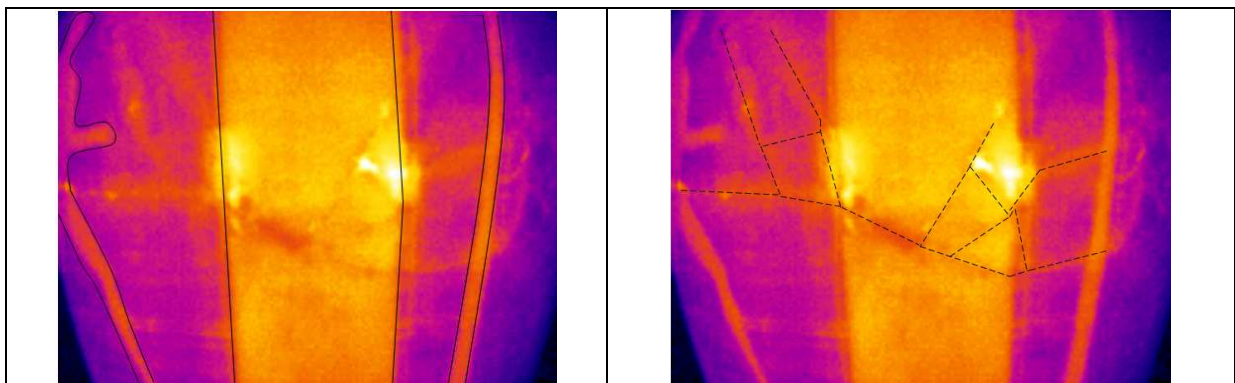


Figure 20: Photothermal image obtained during the photothermal analysis of a face of panathénaïque amphora MNC 7230 (on the left : the photothermal answers of the pictorial layer are underlined on the right : positions of the shards are underlined)

After these encouraging results, we analyzed the base of the Greek “panathénaïque” amphora. The goal of this study was to detect by photothermal method a metal inclusion being used as ballast within the amphora (figure 21 on the left, imagery X). The experimental

conditions were the same as in the previous case. The result of this photothermal study is presented in figure 21 on the right showing significantly different signal in the centre of the base of the amphora, revealing the presence of the in homogeneity which is the metal insert.

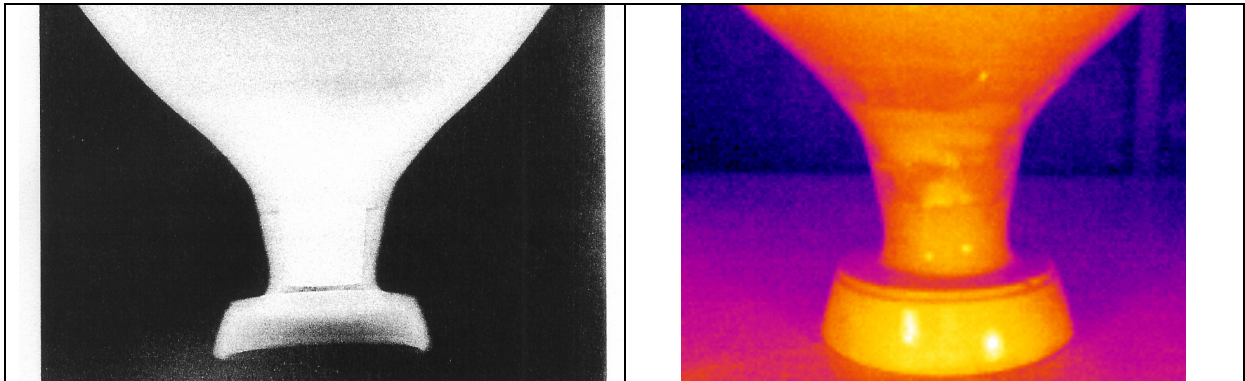


Figure 21: Detection by imagery X (on the left) and photothermal radiometry (on the right) of a metal inclusion in the base of panathénaïque amphora MNC 7230

6.2. Analysis of an ovoid vase (MNC 7235, 1883 AC) of the French National museum of the Ceramics of Sevres

The second type of ceramics work of art that we studied was a fissured ovoid vase. It is dated from 1883 A.D. (figure 22). The vase is fissured in the upper portion pointed out in figure 22. A crack is like a delamination acting as a thermal barrier and is therefore detectable by stimulated infrared thermography.



Figure 22: Studied fissured ovoid vase MNC 7235 of the French National museum of Ceramics

To take advantage of the directionality of the thermal barrier created by the crack, we did not thermally excite the face of the vase uniformly as was done in the other cases. Instead we preferred to use a dissymmetrical excitation, for example, by a flow of hot air applied to the right side of the vase.

The experimental conditions were the use of a pulsed excitation with duration equal to 30s and an excitation power equal to 2000 W. Continuous detection was used with a duration of 180 s.

The results presented in figure 23 represent the photothermal images obtained at various times during the detection process (during the excitation on the left, at the beginning of the cooling of the sample in the centre and at the end of the analysis on the right). They clearly show a blocking of heat at the place of the crack due to its behaviour as a thermal barrier.

Therefore, they show the possibility of detecting this type of defect using photothermal analysis.

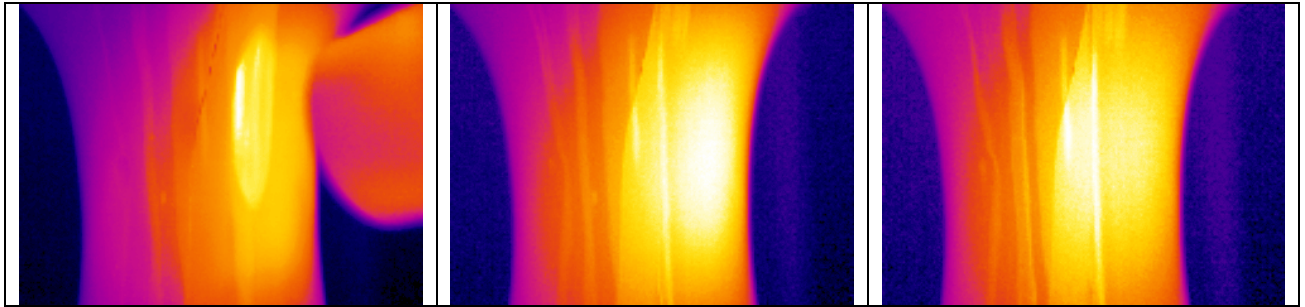


Figure 23: Detection of a crack in vase MNC 7235 by stimulated thermography

7. Conclusion

In this work, we investigated the potential of stimulated infra-red thermography as a means of assistance for the restoration of inheritance works of art.

We initially showed by this technique, the detection of delamination in mural paintings (in an academic fresco and in the «Saint Christophe» of the Campana collection of the Louvre French Museum).

We then showed the detection of delaminations and galleries of worms in marquetrys.

We showed in a third stage, that the technique makes it possible to detect separations of greyness in stained glass.

In a fourth stage, we demonstrated the possibility of visualizing the separate shards or the metal inserts located in a Greek “panathénaïque” amphora of the French National museum of the ceramics of Sevres.

Finally, we showed the possibility of using by this technique to detect a crack located in an ovoid vase of the same National museum of the Ceramics of Sevres.

These very encouraging results now require confirmation and supplementation.

Initially, the photothermal alternative that will lead to the most complete analysis of works of art will need to be determined and implemented.

The less disturbing photothermal stimulus (random excitation?) will then need to be determined.

The quantitative possibilities of the infrared method will still need to be studied as well.

Finally, the analysis procedures will need to be improved to remove the artefacts of detections.

Ongoing work is being performed in these directions.

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