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Examples of singular value decomposition contribution in helping cultural heritage works of art conservation using stimulated infrared thermography

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Abstract

As part of aid for the conservation of cultural heritage works of art, Infrared thermography is already widely used. However, the photothermal signal obtained can be dependent on the different colors of the pictorial layer of the artwork studied and on the inhomogeneity of energy deposition. In this work, we show experimentally, during the study of a marquetry chessboard and a "Vallauris pottery", that the combination of singular value decomposition with stimulated infrared thermography allows a significant reduction of these radiative effects. Consequently, it allows for a better detection of the defects present in the works of art studied.

1. Introduction

Infrared thermography is already widely used in the field of conservation of cultural heritage works of art. It has shown its potential, for example, in the detection of delamination, in the detection of cracks, in the detection of moisture infiltration or in the detection of chemical or biological pollution [1-32]. However, if we restrict ourselves to the analysis of raw thermograms, this method may have certain limitations. For example, the detection of the above-mentioned defects may be disturbed by the different colors of the paint layer or by an inhomogeneity of energy deposition. With the constant increase in computer performance and the progress of mathematical tools for signal processing and image processing, it is possible to associate many new post-processing tools with stimulated infrared thermography. In this work, it is a singular value decomposition that we have chosen to associate with stimulated infrared thermography. The objective of the work presented here is thus to approach the new possibilities offered by this association in terms of aiding the conservation of works of art of cultural heritage. Our presentation is divided into four stages. First, we present the principle of singular value decomposition and explain the interest of its implementation. We then present the two works of art studied: A marquetry chessboard and a "Vallauris pottery from a private collection. In a third step, we present the experimental device implemented for the study and the retained experimental conditions. Finally, we present the experimental results obtained during the photothermal study of these two works of art.

2. Principle and interest of the singular value decomposition

2.1. Principle of singular value decomposition

Singular value decomposition (SVD) is a classic signal processing technique [33]. It allows a signal to be decomposed into the orthogonal basis that is most appropriate, from an energy point of view to the experimental device used to acquire it. It allows the construction of an empirical model of the experiment. It is therefore more natural, from an energy point of view, than the classical Fourier or Laplace transforms. It is of interest in the field of non-destructive testing. This is the reason for its implementation in this study. The principle of an SVD decomposition is as follows: First, we build a rectangular observation matrix X from the thermographic film of the photothermal experiment. It contains m rows and n columns (m > n). The parameter m corresponds to the number of pixels (measurement points) of a thermogram. The parameter n corresponds to the number of thermograms. To build this matrix X, we proceed column by column. In a column we group together all the pixel values of the same thermogram (the scanning of the thermogram is done column by column). It thus corresponds to a moment of measurement. We then scan the entire thermographic film to build the set of columns. Once this observation matrix X is constructed, we proceed to its decomposition into singular values. Then, we use the following formula (1):

$$X = U . \Sigma . V^T \quad (1)$$

In this expression, U is a square matrix with m rows and m columns. Each column is orthogonal to the others. The columns represent the directions of greatest spatial energy variation (in the meaning of signal processing) of the experiment. They represent the axes of the orthonormal empirical basis of the experiment. They are ranked in decreasing order of energy importance. They are called "Empirical orthogonal function" (EOF). Thus the first column of the U-matrix, named EOF1, corresponds to the most energetic direction of the empirical model base of the experiment. Then the second column of the U-matrix, named EOF2, corresponds to the orthogonal direction, energetically just below the previous one. The reasoning thus continues logically to the EOFm column. Σ is a rectangular and diagonal matrix. It has m rows and n columns. The set of values on the diagonal corresponds to the representativeness of the previous Empirical Orthogonal Function (EOF). These values are ranked from the most energetic EOF to the least energetic EOF. Thus the first value Σ1 of the matrix corresponds to the energetic representativeness of EOF1. Similarly, the second value Σ2 (Σ2 < Σ1) of the matrix corresponds to the energy representativeness of EOF2. Again, the reasoning continues logically until the value Σm. V is a square matrix. It has n rows and n columns. Each column is orthogonal to the others. The columns represent the directions of greatest temporal energy variation in the experiment. This representation moves away from the physical representation of the experiment. It is no longer as in the case of the U-matrix homogeneous to a thermogram. It is therefore more difficult to interpret. This explains why we did not consider it in this study. It could however be interesting for the temporal characterization of the depth at which a defect is located.

2.2. Interest of the singular value decomposition

The interest of the SVD decomposition consists in the energetic classification of the EOFs, in order to try to reduce the disturbing effect of the paint layer or of the energy deposition inhomogeneity. The hypothesis is that the photothermal variations due to the presence of defects are, from an energetic point of view (in the sense of signal processing), less important than those due to the inhomogeneity of energy deposition. Therefore, the very first EOFs of the SVD decomposition should show these radiative inhomogeneity. Subsequent EOFs would be less sensitive to them and would rather show the photothermal signature of the defects. Thus, to study the photothermal signatures linked to the defect, we propose to eliminate the very first EOFs, the most energetic ones, and to work only on the following EOFs (within the limit of those presenting a good signal to noise ratio).

3. The works of art studied

Two different works of art were experimentally analyzed in this study. The first is an academic chessboard made of marquetry. The second is a "Vallauris pottery" from a private collection.

3.1. The academic chessboard realized in marquetry

The academic chessboard was made by a cabinet maker for the study. It is made of a 40 cm x 40 cm, 10 mm thick plywood panel. In order to artificially create defects, the surface layer of the plywood was machined in such a way as to create square or sinusoidal gaps in the material. In the first case, the aim is to simulate the presence of delaminations. In the second case, the aim is to simulate worm galleries. There are 9 square faults with different surfaces in order to appreciate the possibilities of the method in terms of spatial resolution of detection. The dimensions of these defects are equal to 3 cm * 3 cm (2 defects), 2 cm * 2 cm (2 defects), 1 cm * 1 cm (3 defects) and 0.5 cm * 0.5 cm (2 defects). They are distributed on the surface of the board. The 3 sinusoidal defects, intended to simulate worm galleries, were made using a 5 mm diameter router bit. They were also placed at different locations on the chessboard (Figure 1).

Fig. 1. *Defects machined inside the support structure of the studied chessboard*

This supporting structure, once it has been provided with its defects, has been covered with a marquetry. This one represents a chessboard and consequently has 64 squares. The light squares are made of oak wood. The dark squares are made of cherry wood leaves. The thickness of the marquetry layers is approximately 1 mm. Finally, the size of a square on the chessboard is approximately 5 cm * 5 cm (Figure 2).

Fig. 2. *The academic chessboard studied*

3.2. The "Vallauris pottery"

The second sample studied is a "Vallauris pottery" (The term "Vallauris pottery" groups together the ceramic production of the workshops and factories set up in the Vallauris region – France- from the end of the 19th century). It comes from a private collection. It is a vase of approximately 35 cm height and 25 cm opening. The diameter of its base is about 12 cm. Its pictorial layer is characteristic of the Vallauris School. It is an extravagant, colorful and reflective paint layer (figure 3).

Fig. 3. *The Vallauris pottery studied*

This vase is cracked. This crack is located in the central part of the vase and is not easily detected by visual analysis (figure 4).

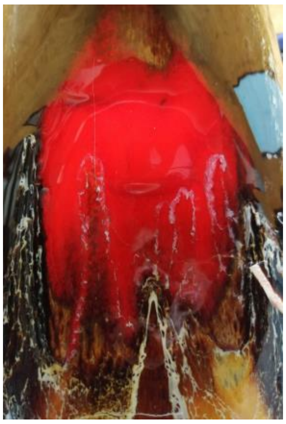

Fig. 4. *The cracked zone studied*

4. The experimental set-up implemented and the experimental conditions retained

4.1. The experimental set-up implemented for the study

The experimental set-up used for the study is composed of two modules. The first module is a data acquisition module. It is composed of the "THERMOART" device developed in the laboratory (figure 5). On the one hand, it allows controlled excitation of the sample being analyzed. On the other hand, it allows synchronous acquisition of the photothermal response of the specimen. The second module of the device used for the study is a data post-processing software package. This is the "IREXPLORER" software package, also developed in the laboratory. It allows an SVD decomposition to be applied to the resulting thermographic film. This can be applied over a user-defined time range. It also provides access to all the EOFs calculated after SVD decomposition (Figures 6 and 7).

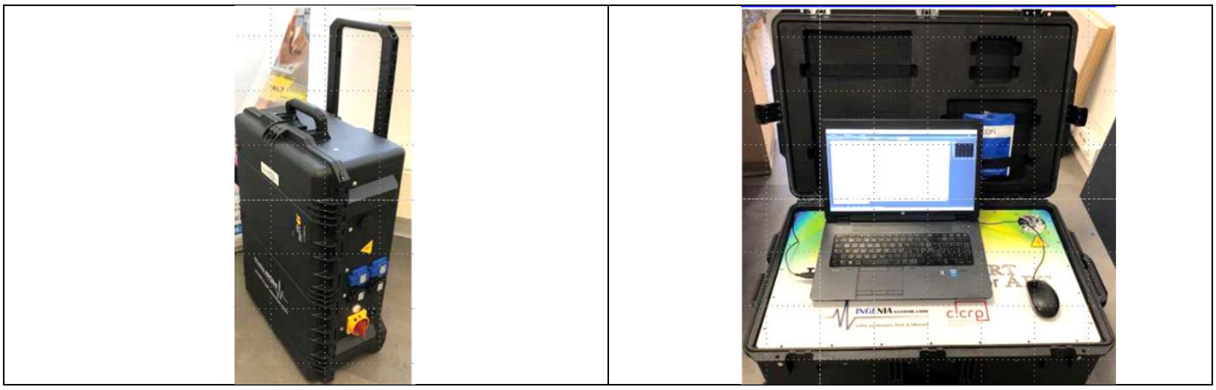

Fig. 5. *The 'THERMOART' system used in the study*

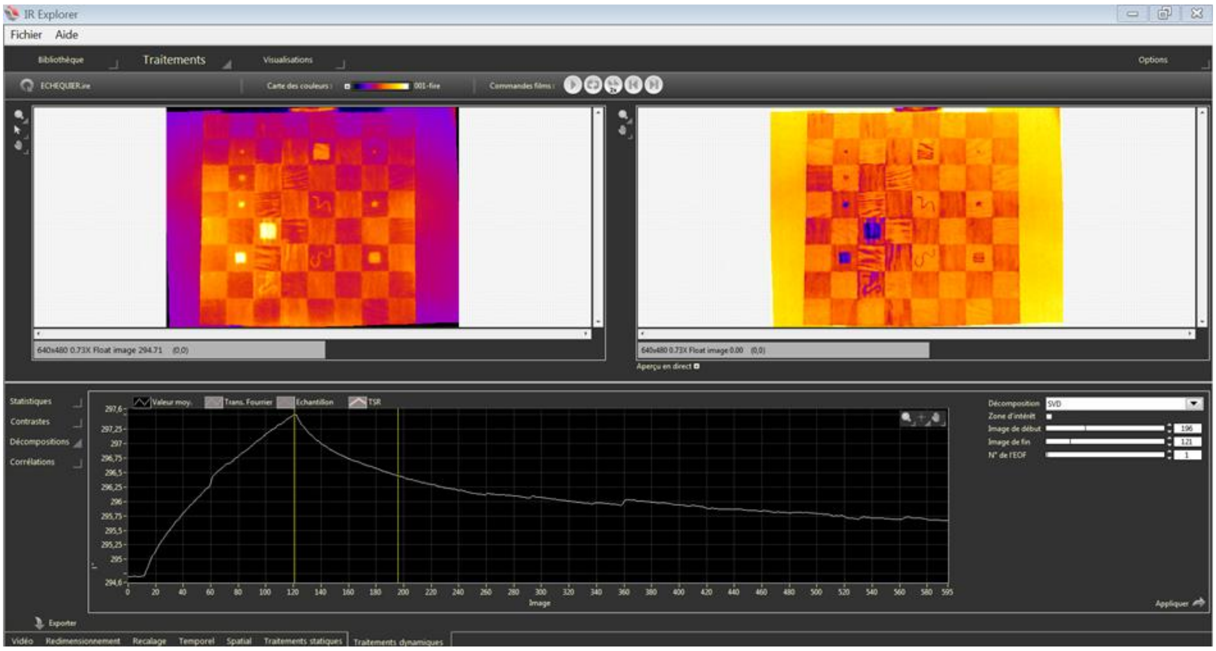

Fig. 6. *Example of the control panel of the "IREPLORER" software package obtained during an SVD analysis of the marquetry chessboard*

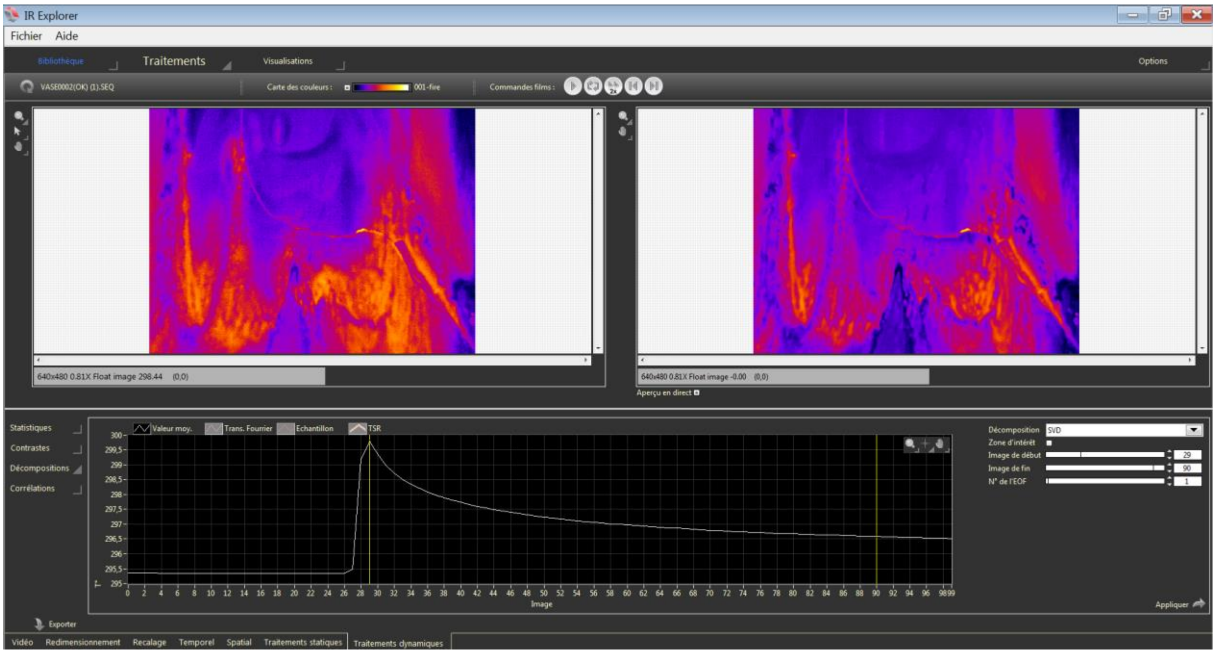

Fig. 7. *Example of the control panel of the "IREPLORER" software package obtained during an SVD analysis of the Vallauris pottery*

4.2. The experimental conditions retained for the study

The experimental conditions retained for the study are as follows: The infrared thermography camera used is the FLIR SC 655. This camera uses bolometers detector. It provides a NETD, and an acquisition frequency sufficient for our study, while keeping a reasonable cost. The optics associated with this infrared camera is a 24.6 mm focal length lens. This choice allows us to obtain a fairly wide field of analysis while preserving a sufficiently resolved defect signature. In order to limit possible radiative, environmental or atmospheric disturbances, this camera is placed perpendicular to the work of art under study.

As far as the excitation sources are concerned, they are different for the study of the two samples analyzed. This is due to the fact that the defects searched for are of different natures (delaminations and worm galleries for the chessboard and cracks for the pottery).

For the study of the chessboard, we chose to use two 250 W halogen lamps. They are placed on both sides of the camera, at about 50 cm from the sample under study. They illuminate the sample at an angle of about 45 degrees along the horizontal axis. This experimental configuration allows for a relatively uniform and sufficient illumination of the area of the artwork under study. The camera is placed at a distance of about 50 cm from the chessboard. The chosen excitation signal is a crenel. Its duration is 10 seconds. The total duration of the analysis is 120 seconds. The acquisition frequency is 10 Hz. Finally, the excitation starts 1 second after the beginning of the thermographic acquisition.

For the study of the "Vallauris pottery", we chose to set up a "ring flash". It is positioned around the lens of the infrared thermography camera at a distance of about 10 cm from the pottery being analyzed. The camera and the ring flash are placed perpendicular to the work of art. The energy deposited is about 1500 joules during approximately 5ms. The acquisition frequency is 50 Hz. The analysis time is 2 seconds.

5. The experimental results obtained

5.1. Example of the academic chessboard

In Figure 8, we show an example of the raw thermogram obtained. It is representative of the results obtained. This is the thermogram obtained at t = 130 s. It shows a more significant photothermal signature in the plumb line of the 9 delamination and of the 3 worm galleries. It therefore shows that stimulated infrared thermography is a good technique for detecting this type of defect. This raw thermogram also shows an inhomogeneous response of the healthy parts of the chessboard. It is weaker in the upper part of the sample and more pronounced in the lateral parts. This reflects the influence of the inhomogeneity of the energy deposition on the photothermal signal.

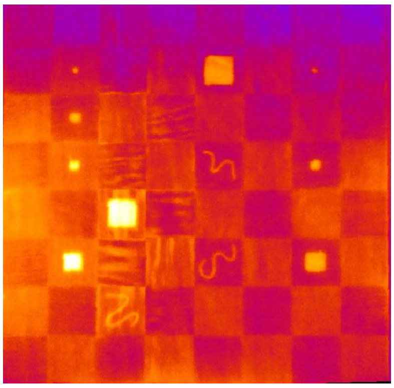

Fig. 8. *Example of a raw thermogram obtained during the analysis of the marquetry chessboard (t = 130 s)*

In Figure 9, we presented the results obtained after an SVD decomposition. The final decomposition was calculated taking into account the first 75 seconds of the cooling phase of the sample studied (from t = 121 s, the beginning of the cooling to t = 196 s). This figure shows the first three EOFs of the SVD decomposition. It shows, firstly, that these synthetic thermograms allow the detection of the twelve defects (more clearly than the raw thermograms). It then shows that if EOF 0 is sensitive to the energy deposition inhomogeneity, EOFs 1 and 2 seem to be much less sensitive to it. Finally, this figure shows that these EOFs allow a good photothermal restitution of the healthy zone of the analyzed chessboard. On the one hand, this makes it possible to obtain information on the healthy zone (wood fibers). On the other hand, it allows an easier localization of the defects present in the work of art studied. This experimental result seems to confirm the interest of an SVD treatment to improve the non-destructive testing of works of art.

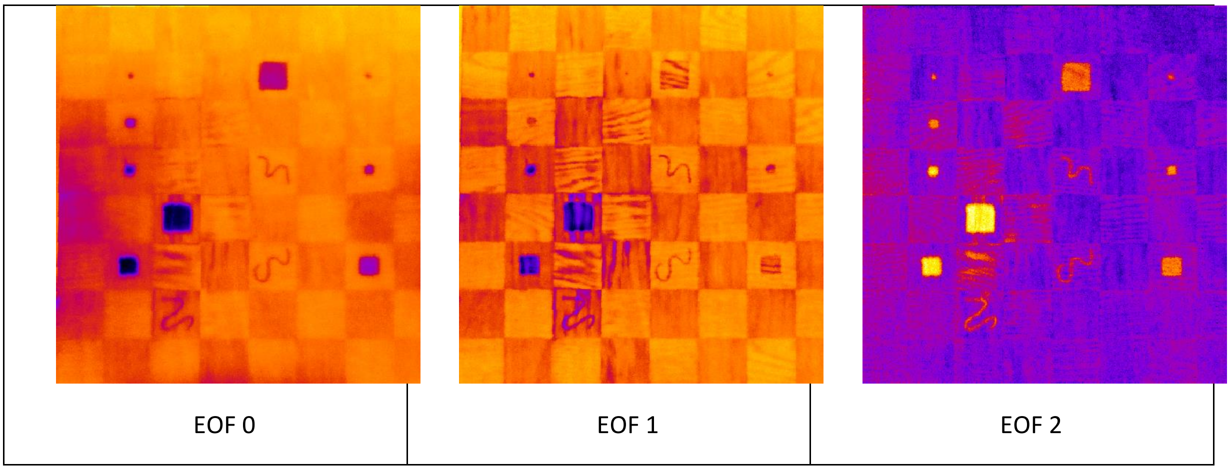

Fig. 9. *The first 3 EOFs obtained during the analysis of the chessboard*
(SVD decomposition calculated between t = 121 s and t = 196 s)

5.2. The "Vallauris pottery".

In Figure 10, we then present an example of a raw thermogram representative of the results obtained during the study of the "Vallauris pottery". This is the thermogram obtained at t = 31 s. It shows a more important photothermal signature at the crack location. It shows that stimulated infrared thermography is also a useful technique for detecting this type of defect. This raw thermogram also shows that it is strongly disturbed by the pictorial layer of the work of art studied. This is a disadvantage.

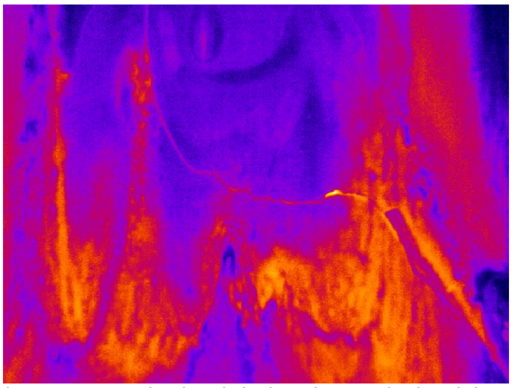

Fig. 10. *Example of a raw thermogram obtained during the analysis of the "Vallauris pottery" (t = 31 s)*

In Figure 11, we present the results obtained after an SVD decomposition. The last one was calculated taking into account the first 61 seconds of the cooling phase of the studied sample (from t = 29 s, beginning of the cooling to t = 90s). This figure shows the first three EOFs of the SVD decomposition. It shows that while EOF 0 is sensitive to energy deposition inhomogeneity, EOFs 1 and 2 seem to be much less sensitive. They therefore allow a better detection of the searched crack. This second experimental result seems to confirm the interest of an SVD treatment to improve the non-destructive testing of artworks.

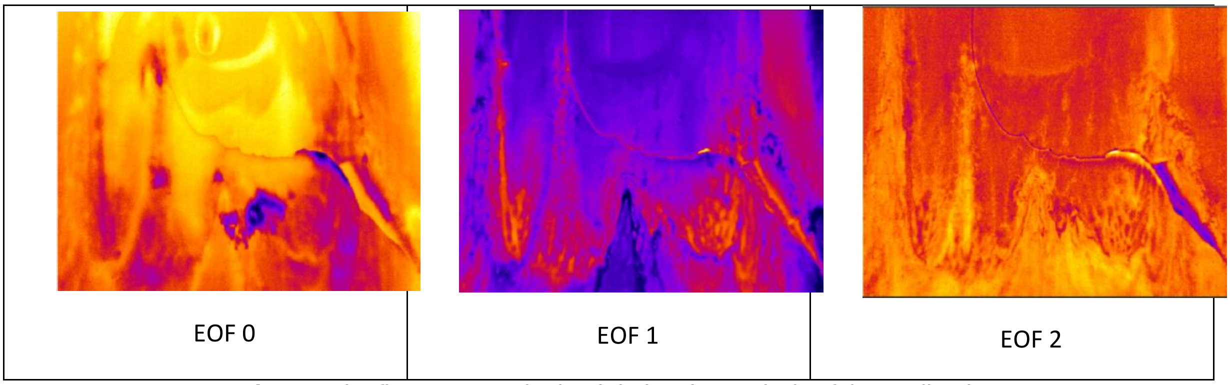

Fig. 11. *The first 3 EOFs obtained during the analysis of the "Vallauris pottery (SVD decomposition calculated between t = 29 s and t = 90 s)*

6. Conclusion

In this work, we approached the contribution of an SVD decomposition to infrared thermography to improve the help of the restoration and conservation of works of art of cultural heritage.

We first recalled that if the non-destructive control of these works of art by stimulated infrared thermography is already very efficient, it could be disturbed, during the photothermal analysis, by the different colors of the pictorial layer but also by the inhomogeneity of the energy deposit.

We then presented the scientific principle of our approach. Our hypothesis consists in considering that the perturbations caused by an inhomogeneity of energy deposition are more important from an energy point of view (in the sense of signal processing) than those due to the presence of defects. In an SVD decomposition, the very first EOFs represent the most energetic fluctuations, while the following EOFs represent the less and less energetic fluctuations. In our case, this means that the analysis of the higher order EOFs should allow us to get rid of some of the energy deposition inhomogeneity and thus, to consider instead the variations of photothermal signals due to the presence of defects.

In order to confirm this hypothesis, we then developed an experimental study on two works of art: a marquetry chessboard and a "Vallauris pottery. In the first case, the results obtained show that an SVD analysis allows a notable attenuation of the inhomogeneity of energy deposition. In the second case, the results obtained show a good attenuation of the parasitic effects induced by the different colors of the paint layer. In both cases, the detection of defects is improved.

These results are very encouraging. They seem to allow the improvement of non-destructive testing of works of art by stimulated infrared thermography. They now require, on the one hand, to be generalized. On the other hand, they need to be confirmed during in situ analysis. Studies going in this direction are in progress.

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