2023 IMEKO TC-4 International Conference on
Metrology for Archaeology and Cultural Heritage
Rome, Italy, October 19-21, 2023

Active infrared thermography for the analysis of ancient books

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***Abstract* – Active infrared thermography has revealed to be an effective technique for non destructive analysis of ancient books. The working principle relies on heating the sample through the absorption of visible light and on subsequent detection of the infrared emission by means of a infrared camera. The technique allows one to investigate features buried into the artworks interior, affecting the heat diffusion inside the sample and inducing a variation in the infrared emission. In particular, it is possible to read written scraps used for the end leafs of old books and located between the end papers and the covers, which is of significant importance for scholars studying the manuscripts. This possibility is discussed in the present paper. A mathematical model for computing the signal contrast and the blurring of the thermographic image of a ink layer buried inside a paper sheet is recalled. Some numerical simulations are presented to asses the effectiveness of the model. Finally, some experimental results are also presented, in qualitative agreement with the theoretical predictions.**

I. INTRODUCTION

Non destructive evaluation techniques are of the outmost importance for the analysis of cultural heritage (CH) items, for obtaining important information about their structure and increase their knowledge, for assessing their maintenance conditions and possibly for evaluating a possible restoration intervention. Accordingly, these techniques are of interest for both scientists studying the manufacts and for restorers. In most cases valuable information are associated to items laying behind the visible surface, which cannot be investigated by means of ordinary optical inspection techniques. For this reason, over the recent years there has been a considerable research work devoted to the development of experimental techniques for the investigation of the features buried into the artworks interior [1]. Among these techniques, the active infrared thermography (IRT) is a very simple and effective tool capable of detecting such kind of items [2]. The working principle relies on heating a sample typically through the absorption of a visible (VIS) light pulse and on subsequent detection of the time history of the induced infrared (IR) emission by means of an IR camera. One peculiar ability of this technique relies in the possibility to distinguish between features located at different depths into the sample, being such a possibility not granted by most of the other techniques employed in the CH field such as IR reflectography [3]. In fact, the pulsed heating is responsible for inducing a temperature variation over a thin volume under the illuminated surface. As time increases, the generated heat diffuses into the inner layers of the sample reaching the inhomogeneities under investigation, which become visible in the detected IR image. In particular, the inhomogeneities become visible after a certain time delay related to the inhomogeneity depth under the illuminated surface. The IRT can be applied both to the study of optically opaque manufacts (metallic items such as ancient bronze statuary) or to optically semi-transparent items (such as ancient manuscripts). In the former case, both the VIS light absorption and IR emission take place in correspondence of the sample surface and, therefore, the IR signal is simply proportional to the temperature variation at the sample surface. Consequently, the time dependence of the IR emission is solely determined by the sample thermal properties. Conversely, in artefacts made of semi-transparent materials such as books both the VIS light absorption and IR emission reaching the camera occur over the sample volume and, therefore, both the sample optical and thermal properties play a crucial role in establishing the time variation in the IR signal [4]. The latter application is the one considered in the present paper. In particular the attention is focused on the possibility of reading hidden texts under the end leafs of old books, which can offer valuable information to both scholars and experts involved in the cultural heritage field. To this end a mathematical model developed by the authors is here recalled. It is able to precisely describe the VIS absorption, three-dimensional heat diffusion and IR emission phenomena in an optically semi-transparent sample with an ink layer buried at a certain depth under the illuminated surface. Several numerical results are reported, to highlight the behavior of the signal contrast and the blurring effect on the IR image of the buried ink layer. Some preliminary experimental results are also illustrated, obtained on an ancient manuscript with containing hidden text. The compar-

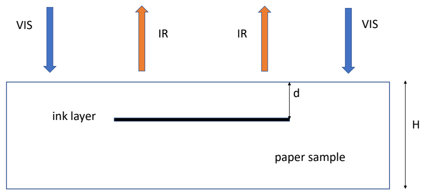

Fig. 1. Schematic representation of the specimen considered in the derivation of the mathematical model.

ison between experimental results and theoretical predictions show a good qualitative agreement for the analysis of the signal contrast and distortion index, the two physical parameters affecting the readability of the hidden text. An exhaustive quantitative study of the readability of hidden texts in ancient manuscripts, buried at different depths, is the object of a forthcoming paper by the same authors.

II. THE MATHEMATICAL MODEL

The mathematical model developed for the description of the IR emission from a semitransparent sample heated by absorption of a VIS light pulse is here briefly recalled. The considered specimen is a thin parallelepiped of thickness H made of paper and containing a rectangulat ink layer of thickness $h << H$, buried at a certain depth d, as depicted in figure 1. Let A, B be the lateral dimensions of the paper and a, b the ink layer lateral dimensions, with $a < A$ and $b < B$.

The heat equation is used to describe heat diffusion inside the specimen. The paper sheet is considered as a tridimensional domain, whereas the ink layer, whose thickness h is negligible with respect to the paper thickness H, is reduced to a two dimensional domain. This is accomplished by applying a concentration of capacity technique to the ink layer, yielding to two dimensional equations for the heat diffusion inside that domain. Heat losses due to convection are permitted on the front and rear surface of the paper specimen, whereas adiabatic conditions are enforced on the lateral boundaries. The excitation light intensity inside the paper is a step function of the time, with duration equal to the pulse duration. In the region containing the ink layer its spatial profile given by:

$$\begin{aligned} I(\overline{x},z) &= I_0(1-R)\mathrm{e}^{-\alpha z} \qquad 0<z<d\,, \\ I(\overline{x},z) &= 0 \qquad d<z<H\,, \end{aligned} \tag{1}$$

where it has been assumed that the ink layer is able to absorb all the VIS lighting reaching it. In the region not containing the ink layer the following expression holds:

$$\begin{aligned} I(\overline{x},z) = {} & \frac{I_0(1-R)}{1-\mathrm{e}^{-2\alpha H}R^2}\mathrm{e}^{-\alpha z} \\ & + \frac{I_0(1-R)R\mathrm{e}^{-2\alpha H}}{1-\mathrm{e}^{-2\alpha H}R^2}\mathrm{e}^{\alpha z} \qquad 0<z<H\,, \end{aligned} \tag{2}$$

where it has been assumed infinite reflections at the front and rear surfaces of the paper specimen [5]. In (1) and (2) z is the vertical coordinate along the paper thickness whereas $\overline{x}$ are the coordinates along the paper plane (assuming a reference system with origin at the centre of the paper front surface and vertical axis pointing downward), R is the reflection coefficient of the front and rear paper surfaces, I_0 is the flash intensity and α is the VIS light volume absorption coefficient of the paper. The volume heat generated at any point inside the paper is given by:

$$-\chi\frac{\partial I}{\partial z}\,, \tag{3}$$

where $\chi < 1$ is a coefficient taking into account the losses due to scattering. The heat generated inside the ink layer is given by:

$$I_0(1-R)\mathrm{e}^{-\alpha d}\,. \tag{4}$$

Once the temperature $T(\overline{x},z,t)$ is computed inside the paper sample as a function of the position $(\overline{x},z)$ and the time t, the infrared signal $S(\overline{x},t)$ detected by the camera can be computed. It is given by the following expression

$$\begin{aligned} S(\overline{x},t) = \kappa \Bigg[& \int_0^d \beta T(\overline{x},z,t)\mathrm{e}^{-\beta z}\,dz + \eta T(\overline{x},d)\mathrm{e}^{-\beta d} \\ & + (1-\eta)\int_d^H \beta T(\overline{x},z,t)\mathrm{e}^{-\beta z}\,dz \Bigg] \end{aligned} \tag{5}$$

relevant to the portion of sample containing the ink layer, where β is the IR volume absorption coefficient, η is the ink layer concentrated emissivity and κ is a scaling constant. The IR emission in the region not containing the ink layer is given by

$$S(\overline{x},t) = \kappa \int_0^H \beta T(\overline{x},z,t)\mathrm{e}^{-\beta z}\,dz\,. \tag{6}$$

The model equations have been numerically solved by applying the finite element method. A program in matlab environment was written to perform all the numerical simulations. Accordingly, the considered specimen is discretized in prisms with triangular bases (paper domain) and in triangles (ink domain), and a finite difference technique is used for the time integration. More details about the mathematical model and and its finite element implementation can be found in [6].

III. EXPERIMENTAL SETUP

In this section the experimental setup used to perform the measurements on an ancient manuscript is described. The manuscript sample was heated by delivering flash pulses of VIS light using two flash lamps of maximum power equal to 3 kW. The lamps where oriented forming an angle of 45^o with respect to the illuminated page, and the pulse duration was approximatively equal to 3 ms. A filter made of a glass cell containing water was put in front of each lamp to prevent the emission in the infrared medium wavelenght (MWIR) produced by the flashes to reach the sample and thus being reflected into the camera. Accordingly the IR radiation revealed by the IR camera is contributed only by the direct emission of the paper sample. A Cedip JADE MWIR camera was used for the acquisition of the sample IR emission, with spatial resolution equal to 320x240 pixels, InSb focal plane array 30 μm pitch and 3.6-5.11 μm wavelength range. The employed camera is characterized by a Noise Equivalent Temperature Difference (NETD) < 25 mK at 30 ^{o}C. The Altair 5.50 software was used to acquire and process the IR images. In particular, the image contrast was enhanced by subtracting the last frame before the flash delivery to all the successive frames. From the processing of the acquired frames it is possible to extract the time history of the signal at any pixel as a function of the time, or the signal along a segment at a certain time, as described in the next section.

IV. RESULTS AND DISCUSSION

In this section some numerical and experimental results are reported, aimed at investigating the possibility of reading hidden text in ancient manuscripts through the use of IRT. Numerical simulations are shown, in order to discuss the dependance of the text readability in terms of the depth d of the ink layer in the paper. The readability of the hidden text depends essentially on two factors: namely the signal contrast of the ink layer and its distortion index. The signal contrast C at any location $\overline{x}$ and at any time t is defined as

$$C(\overline{x},t) = S(\overline{x},t) - S(\overline{x}_0,t)\,, \tag{7}$$

where $\overline{x}_0$ is a location far enough from the ink region, where the IR signal can be assumed not affected by the presence of the ink layer. In order to define and compute the distortion index Δ, let consider a segment crossing the contour of the ink region, as depicted in figure 2.

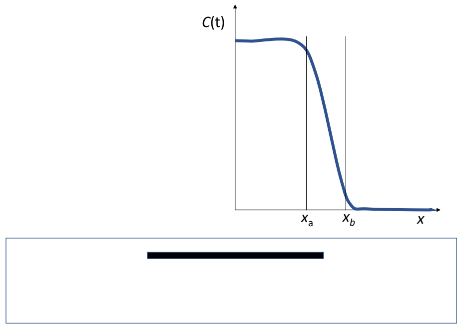

Fig. 2. Definition of the distortion index Δ.

The signal behaviour along the segment at a certain time t is depicted in the figure. Let x_a and x_b be, respectively, the coordinates where the contrast C is equal to 98% and 2% of its maximum value along the segment. The distortion index $\Delta(t)$ is defined as $x_\mathrm{b} - x_\mathrm{a}$ and it has been introduced to evaluate the difference between the detected profile and the step-like one. The simulations reported in the foregoing have been obtained using the parameters values reported in Table 1 of [6]. In figure 3 the signal contrast C is reported as a function of the time t in correspondence of two values of the ink layer depth d. In figure 4 the thermographic signal S is reported, computed at time $t = 0.1$ s, along a segment of length equal to 4 mm perpendicularly crossing the ink layer lateral side, for a depth $d = 110$ μm. Finally, in figure 5 the distortion index Δ is depicted as a function of the time t for the same values of ink layer depths d considered in the previous figure. The irregular behaviour of the curve is due to numerical approximation deriving from the finite mesh size used for performing the simulations

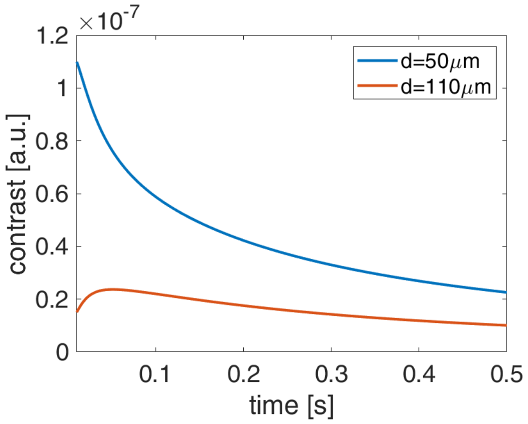

Fig. 3. Signal contrast $C(t)$ versus time in correspondence of $d = 50\mu m$ and $d = 110\mu m$, respectively.

By considering the expression of the IR signal given in (5), two effects contribute to the generation of the signal. The first component is a thermal effect related to the IR emission of the paper, whose temperature evolution is also affected by the heat generated into the ink layer upon absorption of the excitation VIS light pulse. The second effect is an optical one, related to the direct IR emission operated by the ink later, whose emissivity coefficient is larger than the paper emissivity. This second effect makes the ink layer visible in the IR image even if all the specimen is at the same temperature. It can be observed two different behaviours for the contrast curves appearing in figure 3: for

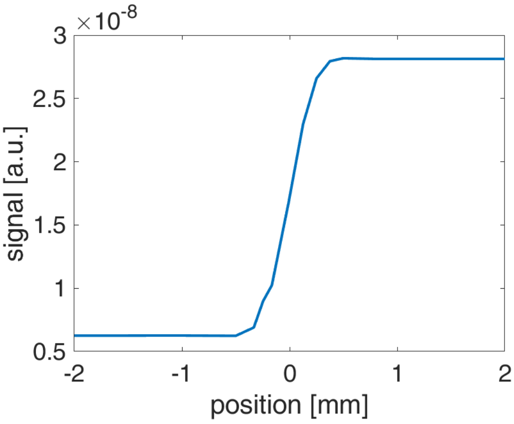

Fig. 4. Thermographic signal S along a segment crossing the ink boundary for $t = 0.1$ s, in correspondence of $d = 110$ μm.

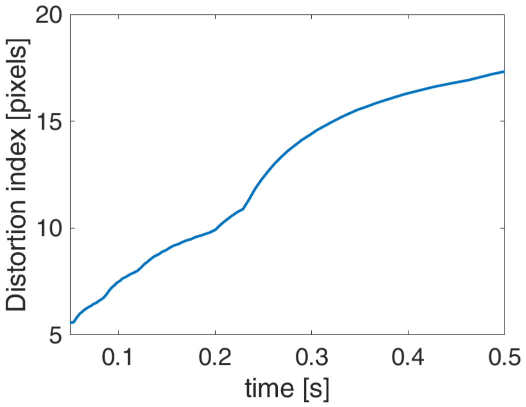

Fig. 5. Distortion Δ versus time t, in correspondence of $d = 110$ μm.

$d = 50\mu$m the second effect (the optical one) is dominant for early times and the contrast curve exhibits a maximum soon after the VIS pulse delivery. For $d = 110\mu$m the first effect (the thermal one) prevails at early times and the contrast curve begins to monotonically increase with time, exhibiting a maximum at a certain time t after the flash delivery. However the second effect is also significatively contributing to the IR signal detected by the camera, and thus the signal contrast soon after the flash delivery has a finite value larger than 0. The larger is the ink layer depth d, the smaller is the initial value of the IR contrast since the second effect contributing to the response is less effective due to attenuation arising in the above paper layer absorbing the ink IR radiation.

The thermographic signal along a segment crossing the ink layer side, reported in figure 4, clearly shows the blurring effect at the lateral interface between ink layer and paper due to heat lateral diffusion, producing a distortion Δ. Though the maximum signal contrast at a fixed time t is strongly affected by the ink layer depth d, the distortion index turns out to depend only from the time t after the flash delivery, as the numerical simulations show. This is related to the fact that the component who essentially affect this parameter is the heat lateral diffusion. The figure 5 reports the distortion index Δ versus time t for $d = 110$ μm but if other curves would be computed for other values of d they would be almost overlapped to the curve shown in the figure.

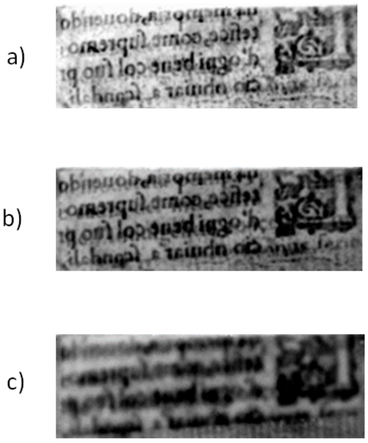

Fig. 6. Experimental detection of hidden text. a) after 0.02 s, b) after 0.04 s, c) after 0.16 s.

Finally, some experimental results are presented, relevant to preliminary measurements on an ancient printing book preserved at the Biblioteca Angelica in Rome. In figure 6 three IR images are reported, representing the detection of an hidden text located at almost 100 μm under the surface of the book end paper. In particular the image a) is taken at 0.02 s after the flash delivery, the image b) is taken at 0.04 s after the flash delivery and, finally, the image c) is taken at 0.16 s after the flash delivery. The image taken at 0.04 s exhibits the greater contrast C but at that time the distortion index prevents a clear readability of the hidden text. The image taken after 0.02 s exhibits a good contrast level together with a reduced blurring of the image due to a low distortion index, and thus allows a clear readability of the hidden text. The last image taken at 0.16 s presents a low contrast with a high distortion index, so the readability of the hidden text is not satisfying.

Finally, in figure 7 the experimental thermographic signal is reported, along a segment crossing an ink letter boundary. The blurring effect is clearly visible, in qualitative agreement with the numerical prediction relevant to figure 4. In a forthcoming paper a quantitative and exhaustive analysis will be presented, for the readability of hidden texts detected on the end leafs of an ancient manuscript.

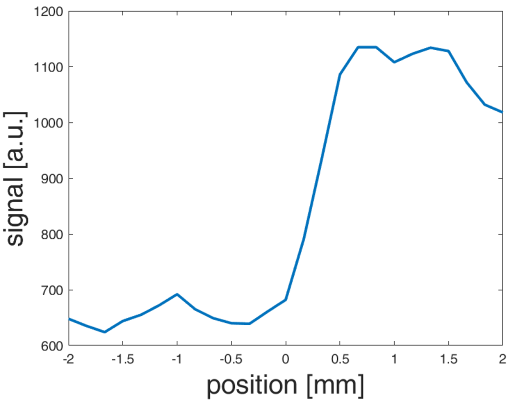

Fig. 7. Experimental signal S along a segment crossing the boundary of an ink letter for 0.1 *s after the flash delivery.*

V. CONCLUSIONS

In this paper the possibility of using IRT as a tool for performing non destructive analysis of cultural heritge items has been addressed. A mathematical model has been briefly recalled, accurately describing the IR emission from a optically semitransparent medium excited by a pulse of VIS light and containing a ink layer buried at a certain depth. The mathematical model has been used to perform numerical simulations for computing the signal contrast and the distortion index of a rectangular ink layer buried at a certain depth inside a paper sheet. In particular the signal contrast soon after the flash delivery exhibits a maximum for sufficiently small values of the ink layer depth d, when the direct IR emission operated by the ink layer prevails on the overall IR signal reaching the camera. For grater values of d the signal contrast reaches a maximum at later times. The distortion index Δ monotonically increases with the time, and turns out to be independent from the ink layer depth d. In fact it is essentially related to the heat lateral diffusion taking place inside the paper. Some preliminary experimental results concerning the detection of a text buried under the end leafs of an ancient manuscript have been also reported. The experimental results turned out to be in qualitative agreement with the theoretical predictions. A quantitative and exhaustive analysis of the readability of hidden texts in ancient books is the object of a forthcoming paper by the same authors.

VI. *

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