METODOLOGY FOR THE EVALUATION OF MEASUREMENT UNCERTAINTY IN THERMOGRAPHICS TESTS – AN APPROACH TO IDENTIFICATION OF INTERNAL DEFECTS IN FRESCOES

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Abstract. *Although extensively presented in several papers as a powerful nondestructive testing method for the evaluation of non visible faults, humidity and other occurrences in works of art, the experimental results obtained from application of thermography have been rarely presented with a coherent uncertainty analysis that allows validating these experimental results. However, infrared thermography is capable of identifying and characterizing imperfections in frescoes, only if, at minimal in a situation of recorded maximum thermal contrast, the differential of temperature existing between the flawed and unflawed area will be greater than uncertainty of measurement on that same areas. The first part of this work presents a methodology for the evaluation of the uncertainty of measurement in thermographic tests. In the second part are presented the results obtained from application of infrared thermography for internal defect detection in frescoes. These results are always been presented correlated with the evaluated measurement uncertainty. The laboratorial tests had been carried out in the Mechanical and Thermal Measurement Laboratory of the Mechanical Department of the Università Politecnica delle Marche – Italy. The samples used have been prepared for specialists in restoration and reproduce the structure and composition of the materials used in frescoes. The internal imperfections had been simulated in order to reproduce a real detachment between the layers of the frescoes.*

Keywords*: Measurement uncertainty, thermographic tests, internal defects in frescoes.*

1. INTRODUCTION

The acknowledgement of the scientific research importance and its applications in the determination of the works of art conservation state has had a great increase with passing of the years, allowing that, in the current days, diverse diagnostics methodologies be available (Tavares, 2006a).

The capacity in identifying non visible elements in structures, humidity, presence of internal imperfections and detachments of the layers that compose frescoes, associated to the low cost of implementation in relation to others techniques consecrated in the sector, as the laser Doppler vibrometry, has placed the infrared thermography (IRT) as a viable option to the cultural goods diagnostic. On the other hand, just a few studies have presented a coherent uncertainty analysis that allows validating the results obtained by technique under this respect.

However, IRT is capable of identifying and characterizing imperfections in frescoes, only if, at minimal in a situation of recorded maximum thermal contrast, the differential of temperature existing between the flawed and unflawed area will be greater than uncertainty of measurement on that same areas.

With the objective to provide metrological trustworthiness to the results obtained from the IRT, avoiding false alarms of irregularities, some works like Chrzanowski *et al.* (2001) and Tavares (2006a) have presented methodologies for determining the uncertainty of the temperature measured by thermal cameras.

In this work, it will be also presented a methodology for the evaluation of the uncertainty of measurement in thermographic tests. Some results obtained from application of IRT for internal defect detection in frescoes samples will be analyzed; always correlated with the evaluated measurement uncertainty.

2. EVALUATION OF MEASUREMENT UNCERTAINTY IN THERMOGRAPHICS TESTS

According to Chrzanowski (2001a), a starting point for the identification of the errors associated to the measurements carried out with thermal cameras is the use of the concepts contained in the “Guide to the expression of uncertainty in measurement” (1993). However, there is still a lack of concluding informations on the methodologies to be employed in the determination of the uncertainties associated to the measurement of temperature without contact. The shortage of works in this area perhaps is associated to the great quantity of variables entailed in the process, each one with specific characteristics. However, according to presented in Tavares (2006a), the first step, in this sense, is the identification of the possible sources of errors that produce the uncertainties.

In case of a process of temperature measurement without contact, the sources of errors that compose the uncertainty of measurement can be divided in external (or of measurement) and internal ones (or intrinsic).

In processes of calibration, where the intrinsic uncertainty of the thermal camera is determined, all the external factors are ignored or known. Such situation is simulated by the use of a blackbody (standard) of great dimensions for the realization of the measures, the maintenance of the minimal possible distance between the thermal camera and the blackbody, in order to have influence of limited transmittance of the atmosphere negligible, the maintenance of the laboratory temperature between 20 and 30ºC and the positioning of the blackbody in the centre of the field of view of the system. The measures must be carried out for the minimal interval of temperature susceptible of being registered by the thermal camera (resolution), and the results presented like an average of, at least, twelve measures. In the determination of the uncertainty, a normal distribution must be assumed (Tavares, 2006a). This methodology is accepted by international laboratories of calibration; it is followed also by the Brazilian organs of calibration.

A set of seven factors is used in the characterization of the intrinsic uncertainty of a thermal camera: minimum error (ME), noise generated error (NGE), digital temperature resolution (DTR), temperature stability (TS), repeatability (RE), measurement uniformity (MU), and measurement spatial resolution (MSR). The methodology described in this study for the determination of each one of these factors and for the determination of the uncertainty of measurement followed the informations contained in Chrzanowski *et al*. (2000), Chrzanowski (2001a), Chrzanowski (2001b), Chrzanowski *et al*. (2001), Chrzanowski and Park (2001), Krapels *et al*. (2002) and Tavares (2006a).

The minimum error, ME, is defined as a range around the output temperature, T_{out}, in which the true temperature, T_{ob}, is located when the measures are executed in conditions of calibration. Though nominated erroneously in the manufacturers catalogues as the indicative of uncertainty, ME can be treated just as the first approximation of the intrinsic uncertainty.

The noise generated error, NGE, is defined as the standard deviation of T_{out} due to noises present in the system. The NGE can be calculated using the value of the NETD (thermal sensitivity) supplied in the manufacturers catalogues. Another option to the NGE calculation takes into account the signal to noise ratio of the electric channel, V_n, and the slope of the system calibration curve, $\partial S/\partial T$:

$$NGE = \frac{V_n}{\partial S / \partial T} \tag{1}$$

where S is the output electrical signal and T the temperature.

The digital temperature resolution, DTR, is the smallest difference between two temperature levels that can be distinguished because of the limited resolution of the digital channel of the thermal camera. This difference depends on the temperature span and on the number of bits of the analog/digital converter of the thermal camera. Due to the non linear dependence of T_{out} of the output electrical signal, DTR is also a function of T_{ob}. However, it is only possible to calculate DTR like a function of T_{ob} when the informations referring to the electronic blocks are perfectly known. Once, most times, these constructive details are limited to the manufacturers, it is necessary assuming a linear dependence of T_{out} on the output signal and to calculate DTR using the Eq. (2):

$$DTR = \frac{\Delta T_{span}}{2^{k_n}} \tag{2}$$

where ΔT_{span} is the temperature span of the camera used during measurements, and k_n is the bit number of the analog/digital converter of the thermal camera.

The temperature stability, TS, is defined as a range in which the results of the measurements carried out in different environment temperatures, within limits determined by the camera manufacturer, are located. Changes of the environment temperature in comparison with the temperature used during the thermal camera calibration causes changes in the output electrical signal. The changes in this signal can be treated like errors of the signal measurement. However, due to the non linear dependence of T_{out} on the electrical signal output, the same signal measurement error can cause different temperature measurement errors. This means that the TS of the thermal camera depends on the temperature of the analyzed object, T_{ob}. Being so, it is necessary to measure TS for different T_{ob}, without the influences of other errors sources, which makes its determination extremely difficult. In this case, it is necessary to use a special large environmental chamber, with perfectly controllable and stable environmental conditions. Since consecutive changes in the environmental conditions are necessary to the tests, to reach the permanent regime in the testing chamber demands great availability of time. On the other side, several temperatures of the blackbody must be tested. Additionally, it is sometimes impossible to achieve a high T_{ob}, principally above 1000ºC, if the temperature in the chamber is quite inferior. To avoid the long time of tests necessary to the TS determination and the mentioned problems, it would be desirable to determine TS for any T_{ob} based on the TS measured for only one value of T_{ob}. This is possible using the Eq. (3):

$$TS\,(T_{ob}) = \frac{TS\,\lfloor T_{ob(m)} \rfloor T_{ob}\; RDRF\,\lfloor T_{ob(m)} \rfloor}{T_{ob(m)}\; RDRF(T_{ob})} \tag{3}$$

where $TS\ (T_{ob})$ is the temperature stability for the object temperature, T_{ob}, $TS\ [T_{ob(m)}]$ is the temperature stability measured for the object temperature, $T_{ob(m)}$, and $RDRF$ is the relative disturbance resistance function of the thermal camera. The RDRF can be defined as the ratio of the relative error of the signal measurement and the relative error of temperature measurement and can be calculated for:

$$RDRF = \frac{\{[dS_{bb}(T_{ob})]/(dT_{ob})\}T_{ob}}{S_{bb}(T_{ob})} = \frac{T_{ob}\int_{\lambda 1}^{\lambda_2} [sys(\lambda)exp(c_2/\lambda T_{ob})] \Big/ \left\{\lambda^6 T_{ob}^2 [exp(c_2/\lambda T_{ob})-1]^2\right\} d\lambda}{\int_{\lambda 1}^{\lambda_2} \{[sys(\lambda)]/\lambda^5 [exp(c_2/\lambda T_{ob})-1]\} d\lambda} \tag{4}$$

where $S_{bb}(T_{ob})$ is the output electrical signal during calibration process of the thermal camera generated by the temperature of the blackbody (in this case, T_{ob}), λ is the wavelength, $sys(\lambda)$ is the relative spectral sensitivity of the camera and C_2 is a constant of value equal to 14387.86 x 10^{-6} m. K.

The repeatability, RE, is defined as a range in which the results of the measurements are located when measurements are repeated under identical measurement conditions. Such conditions must coincide with the conditions used during the determination of ME. Analogously to the TS, RE is a function of the object temperature, T_{ob}. It can be calculated for any temperature of the object based on the value of this parameter measured for a single T_{ob}, using a modified Eq. (3), where TS is substituted by RE. In contrast with TS, RE can be easily measured for different temperatures of the object.

The uniformity of the measurement, MU, is defined as a range in which the results of the measurements are located when the tested object is located at different places within the field of view of the camera. Also it must be determined in the conditions of calibration. As well as RE, MU is a function of the temperature of the object, T_{ob}, being easily measured for a few different values of T_{ob}. Once again, it can be calculated for any temperature of the object based on the value of this parameter measured for a single T_{ob}, using a modified Eq. (3), where TS is substituted by MU.

The measurement spatial resolution, MSR, is defined as the minimum angular dimension of the tested object when there is still no the influences of limited size of this object on temperature measurement results. It is possible to say that if the angular size of the tested object varies, but it is bigger than the MSR, T_{out} remains to same.

Succinctly, it is possible to say that the first six parameters give information about the ranges around the output temperature, T_{out}, in which is the true temperature, T_{ob}, due to different sources of errors like: noise in the analog channel of the thermal camera, limited resolution of the digital channel of the thermal camera, changes of temperature of environment, changes of camera parameters with time, changes of camera parameters within its field of view, and due to all other sources that exist in calibration conditions. The last parameter gives information about the minimal size of the object which temperature can be measured with the thermal camera without fear that results will be affected due to limited size of the tested object.

Most times, these parameters represent for the users a "black box", but it is just through them that it is possible to calculate, using the Eq. (5), the intrinsic combined standard uncertainty, u_{in}, of the thermal camera:

$$u_{int} = \sqrt{u_{ME}^2 + u_{NGE}^2 + u_{DTR}^2 + u_{TS}^2 + u_{RE}^2 + u_{MU}^2} \tag{5}$$

where:

$$u_{ME} = \frac{ME}{\sqrt{12}} \tag{6}$$

$$u_{NGE} = NGE \tag{7}$$

$$u_{DTR} = \frac{DTR}{\sqrt{12}} \tag{8}$$

$$u_{TS} = \frac{TS}{\sqrt{12}} \tag{9}$$

$$u_{RE} = \frac{RE}{\sqrt{12}} \tag{10}$$

$$u_{MU} = \frac{MU}{\sqrt{12}} \tag{11}$$

beeing u_{ME} the partial uncertainty due to the minimal error, u_{NGE} the partial uncertainty due to the noise generated error, u_{DTR} the partial uncertainty due to the digital temperature resolution, u_{TS} the partial uncertainty due to the temperature stability, u_{RE} the partial uncertainty due to the repeatability and u_{MU} the partial uncertainty due to the measurement uniformity.

For u_{ME}, it has been assumed a uniform distribution, once this is the standard proceeding for situations where there is no knowledge on the possible values of the measured inside a certain interval. The same proceeding has been adopted for u_{DTR}, u_{TS}, u_{RE} and u_{MU}. To u_{NGE} has been considered a normal distribution, since the central limit theorem of statistics, when applied to thermal imaging systems demonstrates that the noises distribution generated by the system tends toward a Gaussian shape independently of type of distribution of the noise produced by components of the system.

Analyzing the Eq. (5), it is easily find that the partial uncertainty due to the MSR of the thermal camera is not represented. This means that it was assumed that this partial uncertainty is equal to zero. The assumption about negligible uncertainty of T_{out} due to the limited MSR of the thermal camera was possible because it is admitted that the angular size of the tested object is, normally, higher than the MSR.

However, few civil laboratories have really condition to carry out the calibration of thermal cameras, valuing in the correct form all the intrinsic sources of uncertainty quoted; what takes most of these laboratories to indicate ME being the standard uncertainty of the equipment, according to indicated also in the catalogues.

By other side, the manufacturers, for the characterization of the product, present in their catalogues other parameters than the intrinsic uncertainty calculated according to the Eq. (5). They are the image resolution (IR), the instantaneous field of view (IFOV), the spatial resolution, and the most important when it is wanted to compare equipments: the minimum resolvable temperature difference (MRTD), the minimum detectable temperature difference (MDTD), and the noise equivalent temperature difference (NETD).

The image resolution, IR, presented as a number of pixels or a number of lines per frame, is a good measure of quality of thermal image of the tested object. IR is related to the previously defined measurement spatial resolution, MSR; in spite of this, it is impossible to determine the exact value of the MRS only based on the known image resolution.

The IFOV is defined as the angular dimension of a single detector or the angular dimension of an element of a matrix of detectors. Analogously to the MSR, the IFOV supplies information about the minimum angular size of the tested object for which the influence of the size of the tested object on measurement results is negligible. However, MSR depends on other characteristics of the thermal camera, as refraction of the optical blocks, diffraction effects, and frequency bandwidth of the electrical channel. In this way it is impossible to determine the MSR based only in the IFOV.

The spatial resolution (or the geometrical resolution) is usually measured as angular slit dimension for which the SRF (slit response function) of the thermal camera is equal to 0.5. The SRF is defined as a function of the signal generated by a slit versus the width of the slit normalized to the signal generated by a very wide slit. The spatial resolution defined in this way supplies a good indication of the thermal camera's ability in creating a thermal image. The problem is that the SRF does not supply informations about how much great should be the dimensions of the tested object so that this size does not influence the measurement results. This information is provided by the MSR, also defined as angular slit dimension for which the SRF of the thermal camera is equal to 0.99. Since the MSR is, usually, a few times higher than spatial resolution, the manufacturers prefer to present only values of the first parameter.

The MRTD can be defined as a function of a minimum temperature difference between bars of the standard four-bar-target and the background required by an observer to detect the thermal image of the bars versus spatial frequency of the target.

The MDTD is defined as a function of a minimum temperature difference between a single circular target and the background required by an observer to detect the thermal image of the target versus inverse spatial frequency of the target.

Although MDTD and MRTD are functions, they frequently are presented as single value parameters. In this way, MDTD is normally measured for targets of large size, having values that can vary from 50 % to 70 % of the NETD. For MRTD it is difficult to formulate a similar rule as it is measured for targets of different spatial frequency. If, by a side, MRTD is the most important measure of the ability of a thermal camera to detect and to identify a target, by other side, its use for evaluating measurement thermal cameras, used for absolute temperature measurement, is problematic. Succinctly, it is possible to say that MRTD and MDTD supply some indications about system temperature resolution and about system ability to measure small size objects. However, it is impossible to connect such parameters with the uncertainty of the thermal camera.

The NETD, also presented in the catalogues as thermal sensitivity, provide informations concerning the influence of the electric channel on the measurement errors, which gives a good idea of the uncertainty due to the noises in the system of measurement. It depends on the temperature of the tested object and it is normally measured only for one fixed value, near to 30ºC. So, the NEDT must be corrected when the temperature of the tested object is different from the used in its determination, which can be done using the Eq. (12):

$$NETD(T_{ob}) = NETD(T_{ob} = T_m)\, T_m \frac{\int_{\Delta\lambda} \frac{\partial L(\lambda, T_m)}{\partial T} sys(\lambda) d\lambda}{\int_{\Delta\lambda} \frac{\partial L(\lambda, T_{ob})}{\partial T} sys(\lambda) d} \qquad (12)$$

where T_m is the object temperature for which the NETD was determined and $L(\lambda,T)$ is the Planck's function.

The manufacturers have presented an indicative of the uncertainty of measurement due to noises of the system, on the basis of the known NETD. Assuming a normal distribution for the object temperature, and applying 3σ safety interval, the uncertainty of measurement due to noises of the system can be presented as:

$$u_{NGE} = 3\,.\,NETD(T_{ob}) \qquad (13)$$

According to demonstrated in Chrzanowski (2001a), the application of the Eq. (12) and Eq. (13) provide values for the uncertainty due to noises of the system greater than the typical values for the total uncertainty presented by the manufacturers in their catalogues. This clearly demonstrates that not all intrinsic sources of uncertainty are taken into account in these calculations. Additionally, the factors analyzed by the manufacturers ignore, completely, the effects of the measurement errors (external) and the variation in the thermal camera characteristics with the using time (Chrzanowski *et al.*, 2000).

In real conditions of use, the environmental temperature can vary enough and, even if it is maintained inside of the limits indicated by the manufacturers, from –10 to 40ºC, significant changes in the results can take place due to variations of the radiation emitted by the optical elements of the thermal camera. The environmental temperature influences the temperature of the detectors and, consequently, its sensitivity besides causing the temperature modification of the electronic blocks of the equipment, modifying their behavior and rendering the system unstable. Even in the most modern equipments already equipped with hardware and software that correct the influence of the environmental factors, the problem of the temperature variation regarding the temperature used during the calibration must not be ignored (Balaras and Agariou, 2002).

It is also known that the superficial emissivity of the tested object can vary significantly. In case of works of art, where several materials and/or colors are used, the difficulty in determining the superficial emissivity, its variation inside a same area and the its modifications due to the presence of dirt, have been used, by technicians resistant to the IRT use in the sector, as argument of critique to the technique. Although the problem of the superficial emissivity is real, this effect could be controlled during the image treatment and/or during in situ investigations. The procedure consists in adjusting the emissivity in the thermal camera to indicate the same temperature obtained through a contact technique of lesser uncertainty.

Another potential source of uncertainty of measurement is the atmospheric transmittance. Several particles present on air, like carbon dioxide, ozone and water vapor, can reduce, significantly, the emission of radiation, as well as particles of dust and moisture can cause dispersive effects. A way of minimizing the influences of the atmospheric transmittance is to keep the minimal distance between the thermal camera and the object under observation, which also maximizes the image resolution.

For the evaluation of the combined standard uncertainty of the temperature, $u_c(T_{out})$, measured by the thermal cameras in which the partial uncertainty due to errors of determination of the object effective emissivity, $u(\varepsilon_r)$, the partial uncertainty due to errors of determination of the effective temperature of the background, $u(T_{ba(r)})$, the partial uncertainty due to errors of determination of the effective transmittance of the atmosphere $u(\tau_{a(r)})$, and the intrinsic uncertainty of the thermal camera, u_{in}, are considered, it is suggested the use of the Eq. (14):

$$u_c(T_{out}) = \sqrt{(c_\varepsilon u(\varepsilon_r))^2 + (c_T u(T_{ba(r)}))^2 + (c_\tau u(\tau_{a(r)}))^2 + u_{in}^2} \qquad (14)$$

where the coefficients c_ε, c_T and c_τ correspond to the sensitivity coefficients obtained by the derivative of the function T_{out} (ε, T_{ba}, τ_a). This partial derivative indicates how much the signal of T_{out} vary with the input signals of emissivity, ε, of background temperature, T_{ba}, and of atmospheric transmittance, τ_a. They can be calculated for:

$$c_\varepsilon = -\frac{\int_0^\infty \frac{sys(\lambda)}{\lambda^5\left[exp\left(c_2/\lambda T_{out}\right)-1\right]} d\lambda - \int_0^\infty \frac{sys(\lambda)}{\lambda^5\left[exp\left(c_2/\lambda T_{ba(a)}\right)-1\right]} d\lambda}{\int_0^\infty \frac{\varepsilon_a sys(\lambda) c_2 \, exp\left(c_2/\lambda T_{out}\right)}{\lambda^6 T_{out}^2\left[exp\left(c_2/\lambda T_{out}\right)-1\right]^2} d\lambda} \qquad (15)$$

$$c_T = -\frac{\int_0^\infty \frac{exp(c_2/\lambda T_{ba(a)})(1-\varepsilon_a)sys(\lambda)}{\lambda^6 T_{ba(a)}^2 [exp(c_2/\lambda T_{ba(a)})-1]} d\lambda}{\int_0^\infty \frac{\varepsilon_a sys(\lambda) exp(c_2/\lambda T_{out})}{\lambda^6 T_{out}^2 [exp(c_2/\lambda T_{out})-1]^2} d\lambda} \tag{16}$$

$$c_\tau = -\frac{\int_0^\infty \frac{\varepsilon_a sys(\lambda)}{\lambda^5 [exp(c_2/\lambda T_{out})-1]} d\lambda - \int_0^\infty \frac{(1-\varepsilon_a) sys(\lambda)}{\lambda^5 [exp(c_2/\lambda T_{ba(a)})-1]} d\lambda}{\int_0^\infty \frac{\varepsilon_a \tau_{a(a)} sys(\lambda) c_2 \, exp(c_2/\lambda T_{out})}{\lambda^6 T_{out}^2 [exp(c_2/\lambda T_{out})-1]^2} d\lambda} \tag{17}$$

where $T_{(ba)a}$ is the background temperature during the tests, ε_a is the emissivity of the tested object surface determined during the tests, and $\tau_{a(a)}$ is the transmittance of the atmosphere considered during the tests.

In order to calculate the combined standard uncertainty $u_c(T_{out})$, using the Eq. (14), it is necessary to know not only the coefficients c_ε, c_T and c_τ but also the standard uncertainties $u(\varepsilon_r)$, $u(T_{ba(r)})$ and $u(\tau_{a(r)})$. Although it can be estimated the bounds of the random variables ε, T_{ba}, τ_a, rarely can be estimated the type of distribution of these quantities. Therefore, it can be assumed a uniform distribution of these quantities, once this assumption is commonly made when there is no specific knowledge about possible values of quantity within a certain range. Then the uncertainties $u(\varepsilon_r)$, $u(T_{ba(r)})$ and $u(\tau_{a(r)})$ can be calculated as:

$$u(\varepsilon_r) = \frac{\Delta\varepsilon}{\sqrt{3}} \tag{18}$$

$$u(T_{ba(r)}) = \frac{\Delta T_{ba}}{\sqrt{3}} \tag{19}$$

$$u(\tau_{ba(r)}) = \frac{\Delta\tau}{\sqrt{3}} \tag{20}$$

where $\Delta\varepsilon$, ΔT_{ba} and $\Delta\tau$ are the average standard deviation of each one of the variables.

Chrzanowski (2001a) suggests that, in the calculation of the combined standard uncertainty, should be considered a normal distribution of probabilities, since it is applied the central limit theorem of statistics. This would take T_{ob} to be defined in the interval [$T_{out} - u_c(T_{out}) \le T_{ob} \le T_{out} + u_c(T_{out})$], inside which it is considered true for a level of confidence of 68 %. The expanded uncertainty can be calculated then for a level of confidence 95 %.

3. EXPERIMENTAL PROCEDURES

Measurement sessions were carried out in the Mechanical and Thermal Measurements laboratory of the Mechanical Engineering Department of the Università Politecnica delle Marche - Italy.

The employed sample has been made by a Spanish restorer, Eudald Guillamet, and simulates the typical multi-layer of a so called “buon fresco”. The compact and resistant base of the sample has been fabricated in terracotta, while for the arriccio, a mixture of calcium and thick sand (granulometry of 1÷2 mm) has been used with a ratio of 1:3. For the intonaco, the ratio used was of 1:2.5 and layer thicknesses are 10 and 5 millimeters for arriccio and intonaco respectively. Over the intonaco, a decorative geometric pattern has been painted. A void has been created by mean of very thin foils of communion wafers; the contact of this material with the residual humidity of plaster has caused its almost complete destruction, leaving just some traces of white dust, thus realistically simulating the desired type of flaw. The restorers have indicated approximate values of the diameter (80÷100 mm) and the thickness (1.5÷2.5 mm) of the wafers. Figure 1 shows a schematic view of the sample used in the tests.

The configuration of the thermal bench allows the choice of the distance between the sample and the source of heating (composed of four lamps, each one with power equal to 1000W) and between the thermal camera and the sample. The thermal camera used in this study was a FLIR ThermaCAM™S40. The expanded uncertainty for a level of confidence 95%, according to the last calibration report is of ± 2°C.

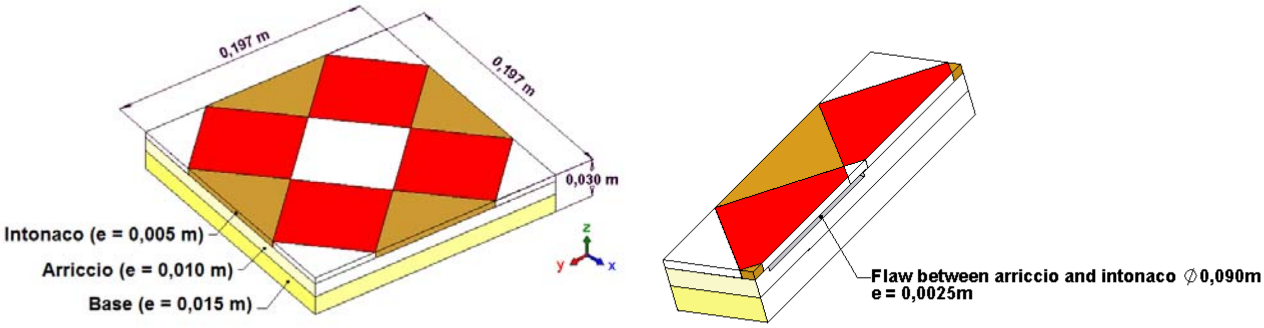

Figure. 1. Fresco sample.

During the thermal experiments, the testing procedure suggested in Tavares (2006a) has been followed. This methodology considers all the diverse variables involved in the measurement process which gives origin to the measurement uncertainty.

The Pulsed Thermography (Maldague, 2000; Carlomagno and Meola, 2002) was employed. The thermal excitement time used was equal to 10 seconds which allowed the uniform heating of the sample surface at a peak temperature that can be considered harmless for the sample (and for a real fresco). The acquisition time was equal to 300s. The distance between the sample and the thermal camera has been kept to 0.55 m and the distance between the sample and the thermal font at 0.20 m. The environment temperature was measured using a thermometer whit expanded uncertainty for 95% equal to ± 0.2^{o}C. The atmospheric transmissivity was considered equal 0.99 ± 0.01. The emissivity of the surface was determined during the adjustment of the thermal camera. This procedure consist in adjusting the emissivity in the thermal camera to indicate the same temperature obtained through contact technique of lesser uncertainty. In this case, thermocouples installed on each different pigment have been used. The expanded uncertainty of the set thermocouple/temperature indicator was determined to be ±0.2^{o}C.

The thermal characteristics of the materials that constitute the sample were considered according to a norm of the ABNT (2003) and information supplied by the restorer. As regards the defected area, the thermal properties of air have been considered (Incropera and DeWitt, 2003). Image analysis has been conducted using the ThermaCAM Researcher 2002®, supplied for the thermal camera manufacturer, and a program developed in MATLAB code.

The analysis was based mainly on the determination of maximum thermal contrast. This because, the best moment for the observation of the presence or not of an anomaly is when the temperature registered by the thermal camera is influenced, more strongly, by the heat transfer by convection to the environment and by the thermal diffusion (Tavares *et al.*, 2006). This situation is represented in the image by the thermal contrast, $C_{(t)}$, which varies with the time and can be calculated from the Eq. (21).

$$C_{(t)} = \frac{T_i(t) - T_i(t_0)}{T_s(t) - T_s(t_0)} \tag{21}$$

where T_i e T_s refer, respectively, to the temperature measured in a point (that is in fact any pixel in the image) over an area with and without defect. $C_{(t)}$ is computed with respect to the distribution of the temperature in the instant (t_0), in relation to the temperature in a subsequent instant (t), and normalized for the condition of the area without defect.

In order to ensure the repeatability of the measurement procedure, the tests were repeated 12 times, under identical testing conditions. This procedure allows data uncertainty analysis.

For the estimate of the combined standard uncertainty, the Eq. (14) was applied in each instant of the sample cooling. The values of the standard uncertainty due to errors of determination of the object effective emissivity, $u(\varepsilon_r)$, of the standard uncertainty due to errors of determination of the effective temperature of the background, $u(T_{ba(r)})$, and of the standard uncertainty due to errors of determination of the effective atmospheric transmittance, $u(\tau_{a(r)})$, were calculated using the Eq. (18) to (20). The parcel referring to the intrinsic standard uncertainty of the thermal camera was obtained of the last calibration report. The sensitivity coefficients were calculated by using the Eq. (15) to (17). The combined standard uncertainty, $u_c(T_{out})$, was expanded for a level of confidence of 95 %. An uniform distribution of probabilities was assumed.

4. RESULTS

Thermal image analysis has been carried out when the thermal contrast peaked at its maximum value, corresponding to the maximum visibility of the defect. The measured thermal contrast obtained during the tests is shown in Fig. 2; its maximum value and the moment in which it occurs have been put in evidence.

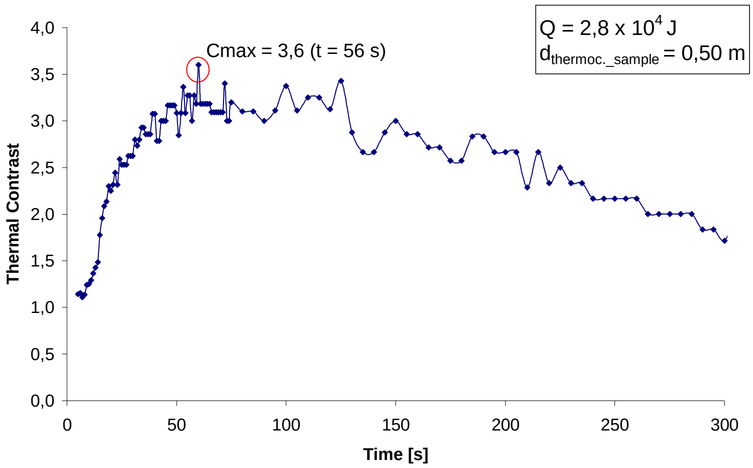

Figure. 2. Thermal contrast

The corresponding thermal maps, obtained by ThermaCAM Researcher 2002 (a) and by MATLAB code (b), can been seen in Fig. 3.

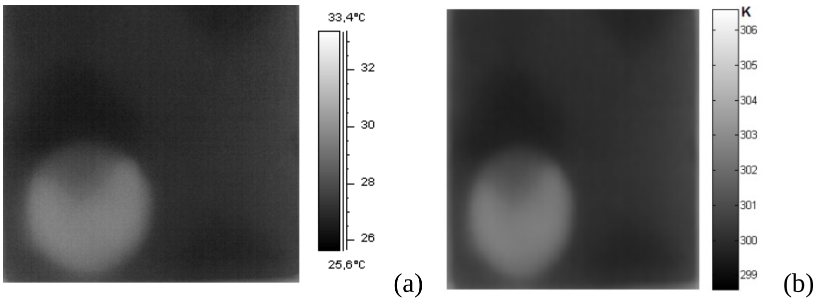

Figure. 3. Temperature maps

The simple appreciation of the thermal image at the moment of the maximal contrast already allows the visual identification of the defect, even considering the low gradient of temperature imposed to the sample by the system of excitement that, in this case, did not surpass 5ºC. By other side, the application of the filters available in the program developed in environment MATLAB minimized the noises of measurement on each pixel of the image, reducing the influence of the colors of the sample surface and resulting in more stable outline of the defect.

However, the real characterization of the defect is only possible comparing the values obtained for the temperature in the flawed and unflawed regions. Figure 4 presents the superficial temperature decay for the two areas. The maximum uncertainty of measurement, expanded to 95%, and calculated according to Eq. (14), was ±1.3°C, as shown in Tab. 1.

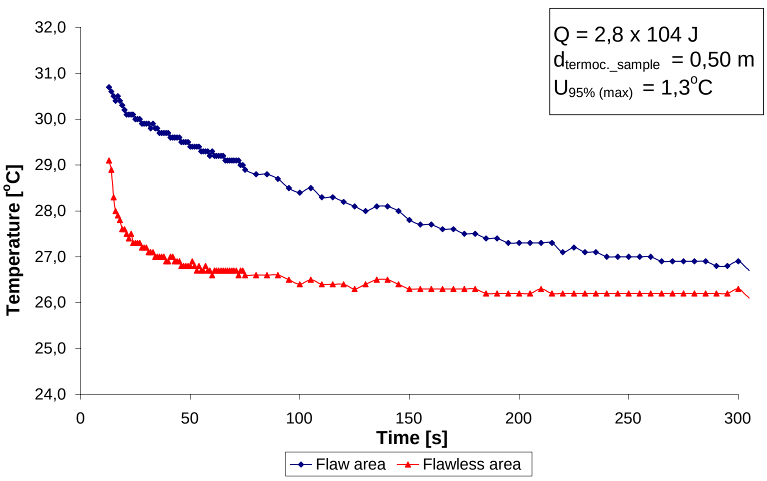

Figure 4. Decay of temperature in flaw and flawless areas

Table 1. Uncertainty calculation spreadsheet

($Q = 2.8 \times 10^4$ J; $d_{termoc.\_sample} = 0.50$ m)

Components of Uncertainty			Type	Probabilities distribution	Divisor	Sensitivity coefficient		u [°C]	ν_i/ν_{eff}
Description	Value	Unity				Value	Unity		
Emissivity(1)	0,01	–	A	Uniform	$\sqrt{3}$	7,467	°C	0,028	11
Temperature(1)	0,1	°C	A	Uniform	$\sqrt{3}$	0,293	–	0,023	11
Transmissivity(1)	0,01	–	A	Uniform	$\sqrt{3}$	46,844	°C	0,146	11
Intrinsic	1,10	°C	B	Normal	2		–	0,550	11
COMBINED STANDARD UNCERTAINTY				→				0,570	12,66
EXPANDED UNCERTAINTY (95%)				→				**1,3**	2,201

(1) Average of indications: $\varepsilon = 0{,}78$; $T = 24{,}6$ °C; $\tau = 0{,}99$; ν_i/ν_{eff} = degrees of liberty/effective degrees of liberty

It can be observe that the cooling curves for flawed and unflawed points are separated, at the moment of maximum contrast, by a difference greater than double the estimated uncertainty, and maintain this trend during almost all the cooling process. This fact guarantees that the defect may be identified in a very certain way.

Very common in thermal analysis applied to works of art diagnostics, the colors effect was also considered in the present work. Although it is not feasible to apply such a procedure in situ, in this study, tests were carried out setting up the thermal camera with an average emissivity value and then using an appropriate emissivity value for each pigment during the phase of image analysis. Anyhow, the temperature difference obtained for the two cases was always lower than the measurement uncertainty.

5. CONCLUSIONS

The aim of this work has been to present a methodology for the evaluation of the uncertainty of measurement in thermographic tests. The results obtained from application of infrared thermography for internal defect detection in frescoes has been also presented. These results are always been presented correlated with the measurement uncertainty evaluated fowling the proposed methodology.

The real characterization of the defect was possible once that the cooling curves for flawed and unflawed points are separated, at the moment of maximum contrast, by a difference greater than double the estimated uncertainty. In percent values, at the moment of maximum thermal contrast, the measurement uncertainty was equal to 41% of the temperature difference between the flawed and unflawed area. This trend was maintained during almost all the cooling process. This fact guarantees that the defect may be identified in a very certain way.

6. ACKNOWLEDGEMENTS

To the CAPES – Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Brazil) for the financing support that permits the realization of the experimental tests.

For the contribution during the experimental tests, the authors thank the staff of the Dipartimento di Meccanica of the Università Politecnica delle Marche.

For the preparation of samples we thank a lot Eudald Guillamet, professional restorer, and Marcel Stefanaggi, from the Laboratoire de Recherche des Monuments Historiques – LRMH, Paris.

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