

Considerations on the preservation of ancient wall paintings by using the Infrared Thermography

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Abstract – The long-term monitoring of ancient wall paintings in historical monuments aims to assess the processes of decay involved, clarify the causes, permit plans of intervention and at the same time control the effectiveness of the restoration works. The paintings are prone to degradation over time. Their decay can arise from humidity, heat transfer, ultraviolet radiation, atmospheric pollutants, microbial agents, bad display or storage conditions, and even physical vibrations. This paper proposes a procedure for analyzing the state of preservation of the frescoes, which also takes into account the state of the walls on which the frescoes are located, the degradation of which has a considerable influence on that of these artistic works, in order to plan any useful restoration work. While the state of frescoes can be evaluated by means of the non-intrusive technique of passive infrared thermography (IRT), the state of the hosting walls can be studied by a quantitative IRT approach (QIRT), which allows a more accurate evaluation. The authors in particular propose an approach based on the estimation of the uncertainty of the measurement of changes in time of the parameters observed through the infrared thermography to more opportunely determine the state of conservation of frescoes and ensure higher reliability in the evaluation of the degradation status over time.

I. INTRODUCTION

The evaluation of the conservation status of frescoes, artefacts, murals of historical/artistic value, as well as historical buildings, can prevent irreversible damage to such works and can also provide significant information for their restoration. Non-destructive testing and evaluation techniques are certainly the most suitable for this purpose. The study, monitoring and structural analysis of artistic artefacts, paintings and historic buildings have been carried out for some years through infrared thermography (IRT). As part of the Cultural Heritage Survey, this technique can, for example, provide

information on the surface and subsurface condition of archaeological sites [1], [2], [3]; it is often used to verify the different nature of the materials of which the artefacts are composed and to verify structural abnormalities of buildings, [4], [5], [6]. In particular, the passive thermographic technique is a valuable tool also for its ability to highlight, in a non-invasive way, archaeological elements hidden through the analysis of the heat transfer process taking place in the object of analysis.

In monitoring the state of preservation of a fresco, painting or mural, it is often forgotten that it is on the walls of a building and that these are themselves subject to chemical/physical degradation over time so furtherly contributing to the degradation of them. Think, for example, of a fresco subject to rising humidity in the wall; the targeted intervention on the portion of the wall that suffers from this problem could prevent future degradation of the fresco. Therefore, to be able to correctly plan restoration work on the fresco, it is necessary to verify also the state of the hosting wall. In this paper, the authors propose combined monitoring to be carried out on the fresco and on the entire wall of the building that houses it, to define, if necessary, the most suitable intervention to plan for obtaining the most correct restoration.

The state of preservation of the fresco is assessed through the classical IRT method, [7], [8], [9], by referring to the non-intrusive investigation. Monitoring of parameters is carried out, under intermediate precision conditions, so evaluating the intermediate accuracy. This approach allows, through pool statistics, to discriminate the need or not to intervene in the investigated object, as illustrated in the following sections. To assess the degradation of the building, instead, the authors propose to trace it from the evaluation of an energy efficiency indicator by means of quantitative infrared thermography (QIRT), considering it more suitable, that is with greater accuracy. The chosen indicator is the transmittance of the wall. This technique is well illustrated in [10] and synthesized in the following section 3, devoted to a brief description of this experimental technique. In particular,

the approach involves the mapping of the temperatures of the wall under investigation, with the possible identification of the hottest and/or coldest points, in the event of an ongoing phenomenon, compared to the surrounding environment within an ROI, as a reference of investigation. By the more correct evaluation of their variations in time (monitoring), a possible anomaly can be discovered by the temperature differences detected in time at those points and visible in a thermal image that represents the temperature map of the object under test, in a suitable color scale. Section 4 is devoted to the case study, a fresco from the Byzantine Church, the preliminary experimental results are described in section 5, and then there are conclusions.

II. EVALUATION OF THE STATE OF PRESERVATION OF THE FRESCO THROUGH THE IRT TECHNIQUE

Monitoring a fresco cannot be separated from monitoring actions of the environment in which it is located and from preliminary investigations of the site. It is of primary importance to keep room temperature, air humidity and ventilation under control. Starting from this simple action that is the basis of the monitoring and measurement activities, we must structure the monitoring of the fresco in a targeted manner and first, we must answer the question: what are the main causes that lead to the sickening of a fresco? Surely the state of conservation of the wall on which it is located and the type of lighting, both artificial and/or natural, on the surface of the fresco are to be highlighted and to be considered as causes of possible damage to the fresco. The greatest damage is caused by the crystallization of the soluble salt in the surface layer, which strongly affects the micro-lesions by producing the disintegration of the plaster and the lifting/detachment of fragments of the surface paint film [11].

Many studies have been conducted to analyze the effect of heat and ultraviolet (UV) light on a painting by showing that inadequate lighting and incorrect exposure to heat sources (including sunlight) can accelerate the degradation of the painting [12], [13]. They promote physic-chemical reactions, causing color fading or darkening and cracking of the paint film. Therefore, even in this case, the preventive conservation strategy is necessary to minimize intervention actions. The damage to the coating layers is therefore a cumulative process due to many factors; it is not easy to discriminate what effect caused the damage, but it can be analyzed and evaluated through the technique of infrared thermography.

Passive infrared thermography is a non-invasive, non-destructive method and is widely used to detect surface defects. Passive thermography, unlike active thermography, does not require external thermal excitation, but rather takes advantage of the different emissive and diffraction capabilities of the simple incident ambient light onto the different areas of the element under

test; for these characteristics is widely used to analyze the state of conservation of fresco [14], [15], [16].

III. HOW AND WHY TO VERIFY THE CHEMICAL-PHYSICAL (HYGROMETRIC) STATE OF THE BUILDING WALL

To date, the non-invasive approach to assessing the energy efficiency of the walls of new or existing buildings is carried out through the qualitative technique of infrared thermography, [17], [18], with the simple detection of the temperatures involved. However, many researchers have been considering the use of quantitative thermography for some time already, [19], [20], [21], which allows a more efficient evaluation of the energy performance of a wall through the quantitative measurement of their temperatures closer to the real values with respect of those estimated by the IRT technique, useful for the more correct determination of the transmittance of the same, chosen as the discriminating parameter of their degradation in time. The thermal transmittance of a wall is calculated by the ratio between the amount of thermal energy exchanged through it per unit area and the temperature difference between indoor and outdoor wall environments. The temperature value, the function of the heat transfer Q through the wall, on the surface of the wall (internal or external) is also due to the heat exchange by convection and radiation with the surrounding environment (the contribution of environmental conduction is obviously ignored). Therefore, it is possible to evaluate the transmittance of the wall by approximating the energy transferred through the wall by conduction with the thermal power exchanged by it with the surrounding environment (energy conservation law). Thus, it can be written, in the most general form, [10]:

$$U = \frac{\left(\begin{array}{l} \sigma \cdot \varepsilon_{tot} [(T_{w_{out}})^4 - (T_{out})^4] + \\ \sigma \cdot \varepsilon'_{tot} [(T_{w_{int}})^4 - (T_{int})^4] + \end{array} \right)}{(T_{int} - T_{out})} \cdot \frac{W}{(m^2 K)} \quad (1)$$

where:

T_{int} is the temperature of the internal environment, T_w is the temperature of the wall surface, T_{out} is the temperature of the external environment, ε_{tot} is the total emissivity (integral emissivity), from which the convective heat transfer coefficient α_c (α'_c) depends and here taken as $3.8054v \frac{W}{m^2 K}$, v being the velocity of the air near the surface; and the Stefan-Boltzman constant $\sigma = 5.67 \cdot 10^{-8} \frac{W}{m^2 K^4}$.

Quantitative thermography can be used, then, to measure the actual temperature of the wall surfaces under investigation, T_w , to obtain a more accurate transmittance value, eqn. (1), the energy performance index of the wall, when the wall in question is that of a building of historical/artistic importance, for which intrusive techniques are not recommended or even prohibited by the

competent office (Superintendence of Fine Arts, in Italy). The thermal camera detects the temperature of a surface due to the reflection of the thermal power radiated by it. To assess the real surface temperature, it is necessary to know the emissivity of the surface, ε_v , which depends on its thermodynamic conditions (mainly the temperature and the degree of humidity).

The measurement of ε_v can be obtained from the law of energy conservation by a direct method, as described in [10], comparing the temperature measurements of a hot source of known emissivity, placed at a distance not exceeding 10 cm from the surface of interest, and the one of its image reflected and visible on the same surface, by using the relationship:

$$\varepsilon_v = 1 - \rho_v \quad (2)$$

where ρ_v is the part of the total energy emitted that is radiated towards the element under investigation, having neglected the part of energy transmitted to the surroundings.

At this point, the measurement of the surface temperature of the test area can be obtained from the thermographic images adjusted with the emissivity value ε_v so estimated.

A second method, more immediate and that provides a good approximation of the real temperature of the wall, consists in using the matte black adhesive tape of which the emissivity is certified (Scotch 88 professional vinyl insulating tape, for example, which emissivity is 0.96 in the regions of short wavelengths (3-5 μm) and long (8-12 μm), [22]. Once the adhesive tape is glued to the wall and reached the thermal equilibrium, the temperature of the tape is measured with the thermal camera, after having set the correct emissivity value. A very good approximation of the actual temperature of the wall can be obtained.

All temperatures required for the procedure shall be measured with the same thermal camera (repeatability conditions) in order to minimise systematic measurement errors.

[23]temperature and the hygrometric degree of the wall, this emissivity value must be evaluated each time before measuring the temperatures. The numerical evaluation of the transmittance through eqn.(1), compared with the values recorded over time with previous measurements, will indicate the degree of decay of the thermal performance of the wall, and then of its degradation, and provide information useful to the influence that the phenomenon can determine on the state of degradation or conservation of the painting (or similar) housed on that wall.

In general, many factors influence the measurement of the U-value of a wall, the most important of which are as follows:

- Climatic conditions of the site, with reference to
 - o moisture values that can significantly alter the thermal performance of the wall;

- o conditioned ventilation in the case of indoor site;

- Operating conditions, in reference to site management by users (heating/cooling and opening/closing windows and/or doors).

Each of these factors should be kept under control or, even better, each of them should be evaluated for the actual influence on the measured quantity as the measurement of transmittance must be performed under repeatability conditions.

The uncertainty to be associated with the temperature measurements is obtained by propagating the uncertainties of all the parameters that affect them, after having carried out enough thermographic measurements to correctly estimate the influence of both precision and systematic effects on the directly measured quantities.

IV. CASE STUDY

The church of Santa Maria della Croce, also known as the "Casaranello" (Fig. 1), represents one of the most ancient monuments in Puglia [23]; it boasts ancient origins ascribable to a dating that oscillates between V-VI century [24], but knew a second very important phase between X and XI century, period in which a decorative cycle of Byzantine frescoes still visible today was realized [25]. The building today has a very irregular basilica-type layout, as result of some important changes that took place over the centuries. Originally the building had a Greek cross design and was perhaps used as a mausoleum [26].

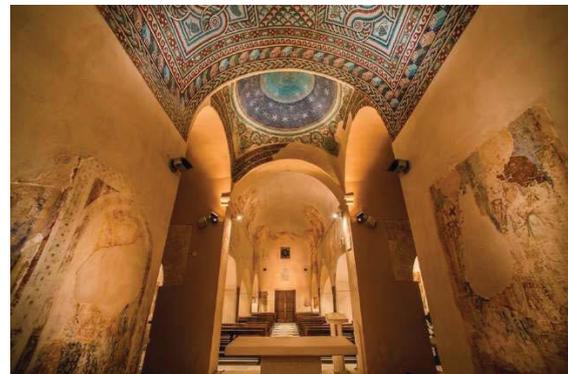


Fig. 1. Inside of the church of Santa Maria della Croce.

Present-day. the church has a plant with three naves divided by pillars joined by arches. A transept, not projecting laterally and in height, introduces, proceeding eastwards, to the presbytery and to the only apse, decidedly protruding and of rectangular layout, this latter obsolete in the early Christian period.

Casaranello has undergone major restoration work, the most invasive of which dates back to the seventies of the last century.

The Late Antique monument is characterized by the presence of wall mosaics (V - VI century) which are comparable only with the most famous decorative cycles of Ravenna. Probably also Casaranello, originally, had the internal walls completely covered by mosaics.

Casaranello also houses numerous frescoes, some made in the Byzantine age (X - XI century), while others dated back to the Middle Ages (from the XII to the XIV century). The general state of the building appears to be satisfactory, and the recent refurbishment of the solar pavement and home automation of the windows for air recirculation, enhance its proper conservation. However, there are still some critical issues resulting from years of disinterest in the monument and the use or abuse that has been made of the church for many years. Artificial lighting is also an important critical factor. The spotlights date back to the eighties of the last century, and point their light beams directly onto the frescoes. Here we have taken as a first example for our study the fresco of Santa Barbara (Figure 2), realized on the second column to the right of the main entrance (Figure 3 and Figure 4).



Fig. 2. Santa Barbara fresco.



Fig. 3. Location of the Santa Barbara fresco.

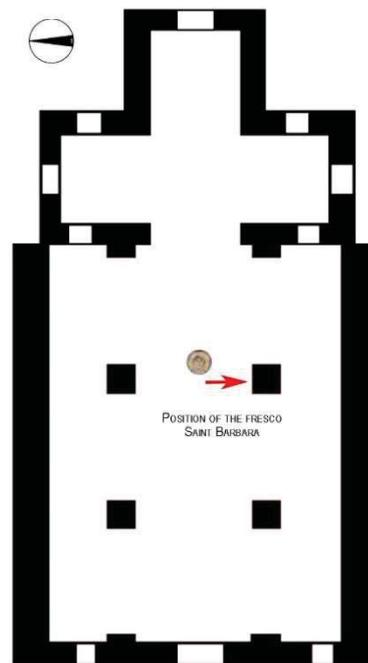


Fig. 4. Plant of the Church. The arrow indicates the location of the fresco of Santa Barbara.

Currently the fresco has a staked surface (Figure 5).



Fig. 5. Detail of the fresco of Santa Barbara

These stakes are ancient and dated back to the eleventh century when the Byzantine rite was replaced (therefore the sacred images were hidden) by the Latin rite (new cycle of frescoes).

There are numerous visible additions on the fresco in question (but also present on almost all the frescoes in the church), made during the restorations (Figure 6).



Fig. 6. Detail of the fresco of Santa Barbara

The colors of the fresco are rather dull and almost faded. Contrary to what it must have been originally, in fact, the Byzantine frescoes always present themselves with intense and rather lively colors. A more accurate analysis of the physical state of the frescoed surfaces will also have to take into account the chemical composition of the different raw materials used.

Environmental factors, as already mentioned above, have certainly not benefited the conservation of the decorated surfaces but have probably accentuated their deterioration.

In addition to what has been said above, the general problems of rising damp or excessively exposed walls should be evaluated.

V. PRELIMINARY RESULTS

The first experimental surveys have been made on the cited fresco of Santa Barbara. The experimental conditions retained for the study are the following:

- Ambient temperature $T_{amb} = 22 \pm 0.5^\circ C$
- Relative humidity $h_{rel} = 58\% \pm 2\%$

Figure 7 depicts the schema of the experimental setup; the distance between the thermal camera and the wall fresco is equal for each of the repeated and replicated experimental acquisitions obtained during the monitoring procedure.

The infrared camera used is a bolometer camera (Flir T1020, IR lens 28° , 36 mm) having a thermal sensitivity enough to detect temperature differences down to 20 mK , 1024×768 resolution, low noise, and a frame rate of 30 Hz .

Figure 8, for example, shows the thermographic image superimposed on the photographic image of the specified zone. The representative thermographic image of the first measurement campaign is obtained by averaging pixel by pixels the thermograms acquired under repeatability conditions.

The thermographic image thus obtained will be compared with the homologous thermographic images acquired in the subsequent experimental surveys.

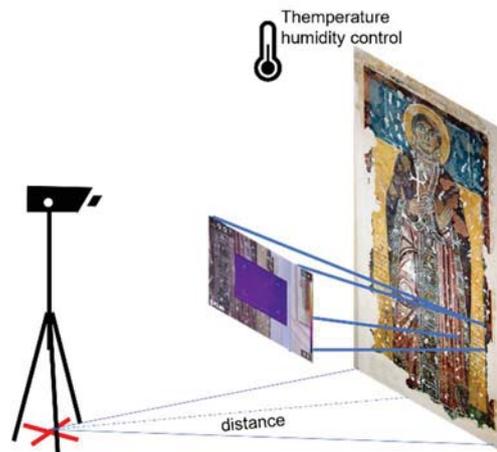


Fig. 7. First step of monitoring procedure

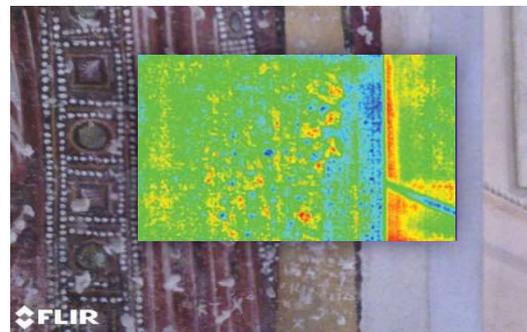


Fig. 8. First step of monitoring procedure

The monitoring, performed periodically (monthly for example), will therefore produce a series of thermographic images on which the regions of interest (ROI) are identified. The evaluated average temperatures of the ROI constitute a temperature map; the difference in temperature detected in the different monitoring maps of each ROI identifies the areas of the fresco that, during the monitoring period, have undergone a possible degradation.

The same measurement procedure can be applied to the hosting wall to infer useful information about the possible degradation affecting the housed artwork, as described above. When this difference exceeds the value of the temperature uncertainty (the fixed threshold), estimated as the GUM states for the intermediate precision [27], the area is considered for a possible restoration.

VI. CONCLUSIONS

By this paper we have intended to explain a non-intrusive technique of monitoring of works of historical and archaeological value, based on thermographic technology, able to prevent irreparable damages to them through preventive interventions of restoration of places. This means not only reducing the risk of damage but also substantially reducing the importance of the restoration works, the related costs of intervention and thus preserving those works that represent cultural heritage.

Preliminary tests have begun on a Byzantine fresco of Santa Barbara placed on an internal column of the nave of the church of Santa Maria della Croce located in Casarano (LE), South Italy, in order to illustrate the procedure that it is intended to implement for a period of time sufficient to demonstrate its reliability and efficiency.

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