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An Emissivity-based Approach to Assess the Integrity State of Archaeological Discoveries by Thermography

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***Abstract* – In this paper the authors propose an innovative technique to evaluate the integrity state of archaeological discoveries by using thermography. The proposed approach is based on the concept of emissivity. The case study is a marble bust of a woman that dates back to ancient Rome. The emissivity of the bust material has been evaluated by using a standardized procedure. To assess the integrity state of the sculpture, the environment temperature has been kept under control to allow the bust to reach thermal equilibrium. By evaluating pixel by pixel, the temperature deviation around the known equilibrium value, it has been possible to map the emissivity changes in the sculpture due to different conservation or decay states: alveolisation process, erosion, damages, deposition of iron oxide, etc. The proposed approach has allowed us to correlate the changes of emissivity with the integrity state of the sculpture. Preliminary studies on the bust provide interesting information about the deterioration from the original condition.**

***Keywords* – thermography; emissivity; integrity state; marble.**

I. INTRODUCTION

Archaeological and historical discoveries are a valuable proof of cultural heritage of peoples and nations. Historical buildings, archaeological sites, sculptures, and ruins are part of our past identity. So, the preservation of their integrity over time is a challenging task because it comes up against the natural degradation process of any material. Depending on the material it is made of and on the conservation environment, the periodic maintenance and monitoring of discovery require appropriate methodologies and measurement techniques, [1], [2]. Measurement science combined with conventional methods and tools used in the field of conservation and restoration of cultural heritage offers new and complementary perspectives for defining effective methods to assure the preservation for centuries and centuries, [3]. Italy has a wide cultural heritage of archaeological discoveries, the conservation of which is a time-consuming task with huge economic costs.

Sensors and transducers are widely used for preserving archaeological heritage by monitoring the integrity of archaeological discovery, [4], [5], [6], [7]. Nevertheless, issues concerning their placement and the resolution of the sensing network can provide non-comprehensive information on the discovery conservation status. This becomes more clear if the extension of the discovery has a big size. Consequently, costs and feasibility become complex aspects. As a result, the use of alternative and non-invasive measurement techniques is recommended to assess the conservation state.

In this paper the authors propose an innovative technique to evaluate the integrity state of archaeological discoveries based on the use of thermography. Thermography is today widely used for environmental monitoring applications, [8], [9]. In the paper, it is described the potentiality of passive thermography in monitoring archaeological discoveries and historic sites, [10], [11]. Due to its history, Italy is the country with the richest amount of historic/archaeological and architectural sites and discoveries. Thermography is in the following proposed as a complementary technique to make reliable and non-invasive assessment of the integrity state of archaeological heritage. Thermal imaging is an effective and valuable tool for detecting defects, erosions, fissures, damages, and material irregularities without any risk for the investigated object, [12], [13]. Advanced uncooled thermal cameras can capture thermal images with high resolution and sensitivity by measuring the radiance emitted by the observed object in the range of the infrared spectrum. The emitted infrared energy depends on the object temperature. The thermal camera converts the measured radiance into temperature values so generating the thermographic image pixel by pixel. The proposed approach is based on the concept of emissivity. Any archaeological discovery which is in perfect conservation conditions and made of a unique material should have the same emissivity for all parts of its surface. If the discovery is in thermal equilibrium, this condition should generate thermal images having uniform colours. However, alveolisation processes, erosions, damages, deposition of iron oxide, defects, fissures, and material irregularities are cause of not uniform emissivity, [14], [15], [16]. Based on this assumption, the authors aim to map the emissivity changes of the discovery due to different conservation or decay states by evaluating pixel by pixel the temperature deviation around the known equilibrium value. The proposed approach has allowed us to correlate the changes of emissivity with the integrity state. Preliminary studies on an ancient marble bust have provided interesting information about its deterioration from the original conditions.

The paper is organized as follows. In Section II, the thermography theory and the discovery under test are described. Section III describes the study and results. Finally, considerations and conclusions are outlined in Section IV.

II. THERMOGRAPHY AND CASE STUDY

A. Thermography and Measurement Setup

Any object having temperature over the absolute zero is able to absorb or emit thermal energy in the Infrared (IR) range of the electromagnetic spectrum ($0.78\ \mu m - 1\ mm$).

The Planck's Radiation Law describes the dependence of the radiance W from the wavelength of radiation λ and the thermodynamic temperature T of the object:

$$W(\lambda, T) = \frac{2\pi hc^2}{\lambda^5}\left[\exp\left(\frac{hc}{\lambda kT}\right) - 1\right]^{-1} \quad (1)$$

where h is the Planck constant, c is the velocity of light in vacuum, k is the Boltzmann constant.

Depending on the material, atoms and molecules may move in specific directions, vibrate, rotate and twist along an axis, see Figure 1. The infrared energy is absorbed or emitted during mechanical interaction. Such interaction increases with the increase of the temperature. Consequently, the emitted radiance depends on temperature in compliance with (1).

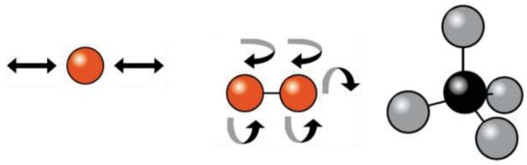

Fig. 1. Atoms interactions.

To evaluate the temperature, the object emissivity must be known. The emissivity value ε_λ can be estimated by the equation:

$$\varepsilon_\lambda = 1 - \tau_\lambda - \rho_\lambda \quad (2)$$

where τ_λ is the transmittance and ρ_λ is the reflectance of the object. A thermal camera is able to measure the radiance emitted by the observed object and to convert it into temperature value generating a thermographic image pixel by pixel.

Figure 2 shows the thermal camera used during the experimentation. It is a high performances *Thermal Infrared Camera FLIR x8400sc* with an Indium Antimonide (InSb) detector, a resolution of 1280x1024 pixels, a frame rate up to 106 Hz, a temperature range [-20 3000] °C, a spectral range of [1.5 5.1] µm, and a sensitivity smaller than 18 mK.

Fig. 2. Infrared thermal imaging camera, FLIR x8400sc.

Several thermal imaging techniques have been defined depending on the specific application and scope. Passive and active thermography represent the main classification of such techniques. Passive thermography allows to measure the radiance of the object without using any external thermal excitation system. Typically, this technique is used to analyse the temperature gradient distribution over time. Active thermography needs an auxiliary thermal solicitation system to analyse the thermal response of the object over time. This technique allows to obtain relevant information about the object in presence of parts having a different thermal response. Other advanced techniques such as lock-in IR thermography and spectral thermography use specific processing algorithms to extract detailed information about the object properties.

B. Case Study: a marble bust of ancient Rome

The considered case study concerns a marble bust of a woman that dates back to ancient Rome preserved at the Archaeological Superintendence of Reggio Calabria, Italy. The bust, clearly comparable with the portraits of Crispina (about 180-187 A.D.) for the peculiar second hairstyle worn by the wife of the emperor Commodus and the first *Iulia Domna*'s representations (193-211 d.C.), with the thick hair parted in the centre of the forehead, the wavy locks combed back and the voluminous chignon at the nape of the neck is striking for the intensity of the gaze, determined by the three-quarter position of the face and the size and depth of the pupils, a typical feature of the late Antonine and first Severian age. The blows that deliberately damaged the nose and mouth are clearly visible, perhaps caused by the pickaxe during its discovery or maybe we could considered as a form of *damnatio memoriae*, see Figure 3.

Fig. 3. Woman marble bust dated back to ancient Rome.

III. STUDY AND RESULTS

The discovery, preserved in excellent condition, has been subjected to cleaning. Preliminary analysis has highlighted the presence of further cuts on the bust, especially in the back and under the hair. These surface damages are not cracks, they are probably attempts at working with marble and therefore due to the hand of man.

The integrity state of the bust was analysed by using passive thermography. To this aim, the sculpture has been placed on a support. The temperature of the environment has been kept under control in order to allow the bust to achieve thermal equilibrium. The background has been covered using a black cotton cloth so to avoid any interference during the thermographic measurements. Attention has been paid to any direct irradiation source to limit reflected radiation.

Figure 4 reports a thermographic image of the bust. Although the sculpture is in thermal equilibrium, it is possible to observe in the thermographic image an apparent temperature gradient on the surface. The result is the effect of parts of the bust having different conservation states: alveolisation process, erosion, damages, deposition of iron oxide, etc. As a result, the marble sculpture has different emissivity values depending on the conservation state of each part. The changes of emissivity are cause of different apparent temperature values depicted in Figure 4 with different shades of colour. Such emissivity changes can be emphasised, as in Figure 5, by choosing different colour palettes so increasing the contrast between the undamaged parts (preserving the original state) and the parts having different signs of deterioration: alveolisation (the neck), erosion (the head), damages (the mouth and nose), deposition of iron oxide (the breast and parts of chest).

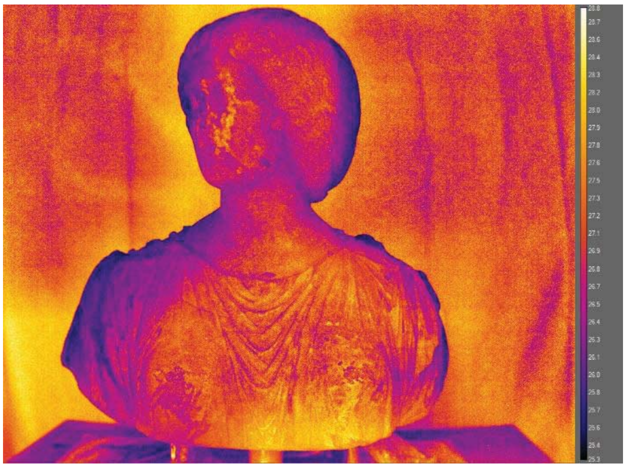

Fig. 4. Thermographic image of the marble bust.

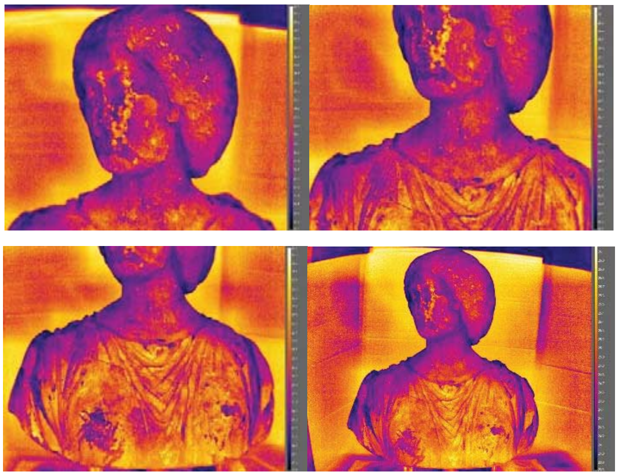

Fig. 5. Thermographic images of the marble bust.

To measure the original emissivity of the marble, the bust has been accurately analysed in order to detect the parts having the best conservation state in compliance with its original state. Consequently, little pieces of ScotchTM Brand 88 black vinyl electrical tape with known emissivity of 0.96 have been glued on undamaged portions of the sculpture waiting for thermal equilibrium, see Figures 6 and 7 for reference. By setting the emissivity parameter of the thermal camera to that of the known material, the absolute temperatures of both materials (Scotch tape and undamaged marble) have been put in comparison, see Figure 8. The surface emissivity value of the undamaged parts of the sculpture has been estimated by making equal the acquired temperature values of the tape and of the marble surface near it.

Fig. 6. Black vinyl electrical tape used for the emissivity estimation.

Fig. 7. Details of undamaged portions of the bust.

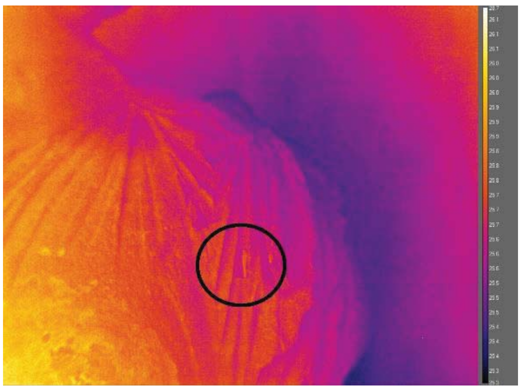

Fig. 8. Thermographic image of an undamaged part of the bust.

The estimated equilibrium temperature of the marble is equal to 25.4°C, and its evaluated original emissivity value is equal to 0.91. This value has taken as reference in order to evaluate the deterioration level of different parts of the sculpture from the undamaged ones. A new colour palette has been created by performing a classification of the temperature range 25-26 °C. The temperature range has been divided into 10 uniform classes assigning a colour from black to white as depicted in the colour bar on the right side of the Figure 9.

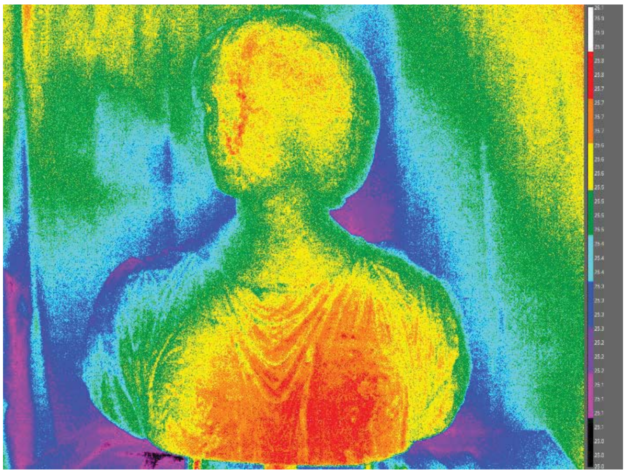

Fig. 9. New colour palette and temperature classes.

This figure allows us to describe the emissivity changes compared to the reference value of 0.91. The areas having the reference emissivity are depicted in light blue colour (fifth class); these represent the undamaged parts of the sculpture preserving their original conditions. Different emissivity values have been depicted with different colours pixel by pixel so characterizing the deviation from the original conditions. Figure 10 shows the histogram of the number of pixels having a temperature value belonging to each class. This figure provides quantitative information on sculpture deterioration state.

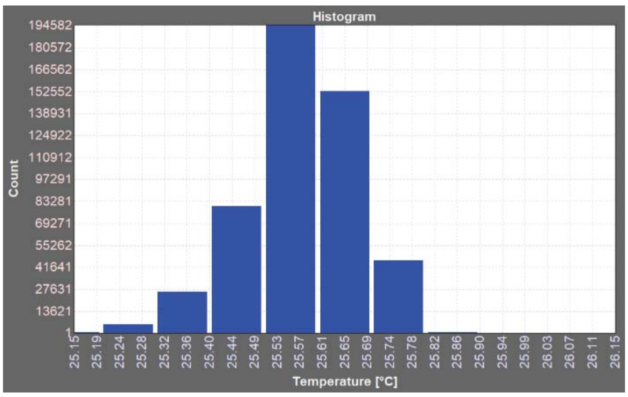

Fig. 10. Histogram of pixel distribution in the classes.

The analysis of the histogram allows to assert that about 16% of the bust surface (front part) maintains its original state, whereas 84% of its surface has signs of deterioration due to different decay processes.

Experimentation is currently in progress to correlate the emissivity changes with each specific decay process. The final aim is to provide a diagnostic tool mapping the deterioration state and the decay process of the discovery so to assist operators during the restoration process.

IV. CONCLUSIONS AND FUTURE WORKS

In this paper the authors have proposed an innovative measurement technique based on thermography to evaluate the conservation and degradation state of archaeological discoveries. The idea is to use the changes of the thermal response due to different degradation states as well as alveolisation, erosion, damages, and deposition of iron oxide. Indeed, all these decay signs are cause of changes of emissivity with respect to the original value which characterizes the undamaged parts of the discovery. Consequently, this is cause of apparent changes of the surface temperature which are clearly visible in the thermographic image even if the discovery is in thermal equilibrium.

The proposed technique has been validated on a case study. The considered archaeological discovery is a marble bust of a woman that dates back to ancient Rome preserved at the Archaeological Superintendence of Reggio Calabria, Italy. The original emissivity of the marble has been evaluated by using a standardized procedure. This reference value has been used to characterize the temperature deviation from the expected value for each pixel of the thermographic image. Such temperature deviation is directly correlated to the emissivity changes due to degradation and decay processes.

Results have shown the effectiveness of the proposed diagnostic technique. It has allowed us to get quantitative information on the total deterioration state of the discovery by quantifying the number of pixels having a different value of temperature with respect to the equilibrium temperature. Although a higher degradation level is not strictly correlated to a higher deviation of temperature/emissivity from the reference value, the histogram associated to the temperature deviation could help to perform a classification about the specific decay or degradation process. Future work aims to correlate the emissivity changes to the different degradation type as well as alveolisation, erosion, damages, and deposition of iron oxide. To this aim, further experimentation is currently in progress. The final goal is to provide a diagnostic tool for assisting the restoration process.

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