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Characterization of material alterations in archaeological discoveries using thermography and emissivity changes

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ABSTRACT
The present paper reports the results of a study focused on the characterization of the material alterations in archaeological discoveries. The proposed approach is based on the thermographic analysis of the thermal response of the different parts affected by degradation or alterations such as alveolisation process, erosion, damages, and deposition of iron oxide. Material alterations are characterized by changes of emissivity. Consequently, thermographic images show significant differences in the temperature values even if the object is in thermal equilibrium. This apparent temperature variation can be characterized and compensated by evaluating the emissivity of each part having material alteration. Material alterations are not always visible at naked eye and are even responsible for changes of the dynamic thermal response when external thermal solicitations happen. The erroneous interpretation of such features is inevitably cause of an incorrect analysis of data with consequent altered results. The paper focuses on this issue to advise operators to pay attention to such aspects. The proposed case study is a marble bust of a woman that dates back to ancient Rome. The results show the need to characterize the presence of material alterations by analysing the thermal response in static and dynamic conditions. Recommendations are provided to compensate the thermal changes in thermographic images by assessing emissivity variations.

Section: RESEARCH PAPER

Keywords: thermography; emissivity; material alterations; archaeological discoveries

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1. INTRODUCTION

Monitoring of archaeological and historical discoveries is an important task to preserve their integrity over time. Depending on the type of archaeological heritage (archaeological site, sculptures, ruins or historical buildings, artifacts …) this task may be more or less complex. Appropriate methodologies and measurement techniques can support the periodic monitoring process by offering complementary perspectives, [1]. The definition of new effective and low-cost methods is basic to reduce the burden due to heritage preservation, [2], [3]. This becomes more compelling if countries like Italy, Egypt and Greece are considered, [4], [5], [6], [7], [8], [9]. The width of archaeological discoveries in these countries is the cause of huge economic costs, and this makes the monitoring unsustainable, [10]. For example, the use of sensors and transducers entails several issues concerning the numbers of nodes and the real-time processing of data, and often information can be non-comprehensive about the real conservation status of the discovery. In this paper, the authors aim to propose an alternative and non-invasive measurement technique based on thermography to evaluate the integrity state of archaeological discoveries, [11], [12], [13], [14]. In previous studies, we have proposed the use of passive thermography, [15], [16], as in [17], [18], to assess the conservation state of a bust and historical artifacts. In this paper, we aim to characterize the different thermal responses to external stimuli related to different material alterations. The authors in [19], have shown that alveolisation processes, erosions, damages, deposition of iron oxide, defects, fissures, and material irregularities are caused by non-uniform emissivity of the material. In other words, even if the object is in thermal equilibrium, this condition generates thermal images having non-uniform colours. As a consequence, the map of the temperature changes is directly correlated to the emissivity changes of the discovery due to different conservation or decay states. Attention is here focused on the dynamic response to external thermal stimuli, in order to understand the behaviour in terms of heat transfer in the presence of several material alterations like alveolisation and deposition of iron oxide.

The proposed approach is based on the analysis of the temperature deviation around the known equilibrium value. In detail, any archaeological discovery made of a unique material and having a perfect conservation state should be characterized by a uniform emissivity, [20], [21] and [22]. Any change can be attributed to changes in the integrity state of archaeological heritage. So thermal imaging becomes an effective and valuable tool for detecting defects, damages and material alterations. In [19], authors have proved the correlation between changes in emissivity and the integrity state. The case study is an ancient marble bust. Its integrity has been previously investigated by using passive thermography. In the present paper, active thermography is used to characterize the dynamic response to thermal excitation to provide complementary information about the material alterations of the bust. These studies on the sculpture have provided interesting information about its conservation state from the original conditions so proving the relevance of the proposed technique.

The paper is organized as follows. In Section 2, the case study is described. Section 3 reports the results. Finally, considerations and conclusions are outlined in Section 4.

2. A MARBLE BUST OF ANCIENT ROME

A marble bust of a woman is the considered case study, see Figure 1. The sculpture dates back to ancient Rome and it is preserved at the Archaeological Superintendence of Reggio Calabria, Italy. It represents the portraits of Crispina, the wife of the emperor Commodus. It is recognizable due to the peculiar hairstyle worn by Crispina, then it is dated 180-187 A.D. The bust is characterized by the thick hair parted in the centre of the forehead with a voluminous chignon at the nape of the neck. The face has a three-quarter position and shows an admirable intensity of the gaze which is a typical feature of the late Antonine age. Damages in the nose and mouth areas are clearly visible. It is supposed that they are the consequences of *damnatio memoriae*. Overall the statue is preserved in good external condition. Its integrity has been analysed in [19] by using passive thermography. In this previous study, the sculpture was placed on a pedestal, and the ambient temperature was kept constant in order to let the bust reach thermal stability. Precautions have been taken to avoid common measurement interference and errors. In particular, black cotton cloth has been used to cover the background to limit the direct or reflected infrared radiation, thus avoiding artificial and natural irradiation due to the light sources. The measurement setups include a high-performance *Thermal Infrared Camera FLIR x8400sc*. It has an Indium Antimonide (InSb) detector with an image resolution of 1280 × 1024 pixels. The spectral range belongs to the interval [1.5 5.1] μm, and the sensitivity is smaller than 18 mK. Figure 2 shows two thermographic snapshots of the bust in thermal equilibrium.

The previous images show clearly different temperature levels on the bust surface depicted by different colour gradations. That is the result of apparent changes in temperature due to material alterations. Alterations of the conservation states due to alveolisation and deposition of iron oxide are caused by changes in surface emissivity, see Figure 3. The sculpture shows several deteriorated parts such as the neck (alveolisation), the head (erosion), the mouth and nose (damages), the breast and parts of the chest (deposition of iron oxide). Areas having different emissivity values are characterized by different apparent temperature values as in Figure 2.

Although the bust is entirely made of marble, different conservation states of each part alter the original emissivity of marble. So processes such as alveolisation process, erosion, damages, deposition of iron oxide, etc can be characterized by evaluating the changes of emissivity which are clearly visible in the thermographic images by means of different shades of

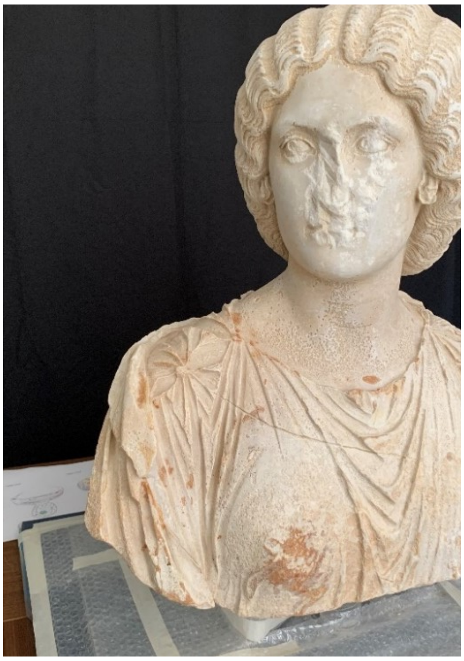

Figure 1. The case study: a marble bust of ancient Rome of Crispina, the wife of the emperor Commodus (180-187 A.D.).

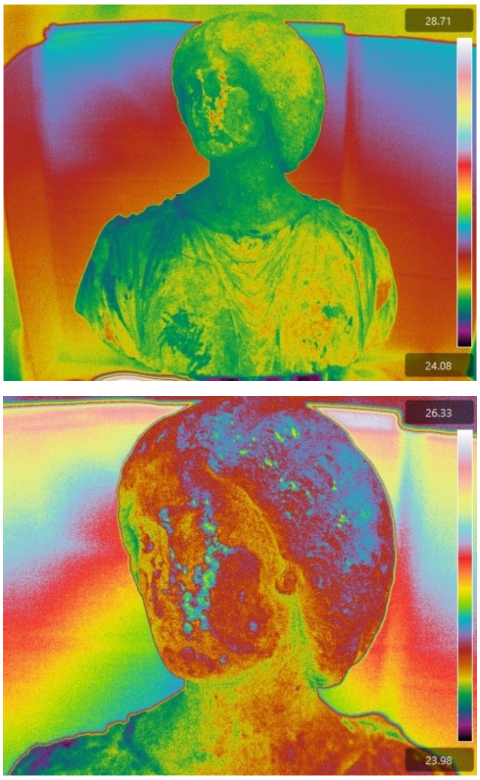

Figure 2. Thermographic images of the marble bust.

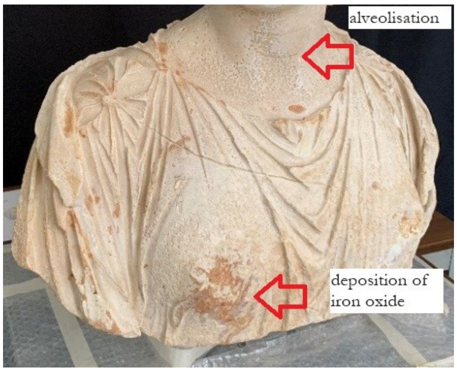

Figure 3. Details of alterations type in the marble bust.

colour. The choice of proper colour palettes it ~~is~~ possible to highlight the contrast between the parts of the sculpture preserving the original state and the other ones having signs of deterioration.

In [19], the original emissivity of the marble has been estimated by using the procedure of the vinyl electrical tape. Some parts having perfect conservation state have been detected. It has been supposed that these parts have maintained the original state of marble conservation. Small fragments of ScotchTM Brand 88 black vinyl electrical tape have been glued on the parts of the bust preserving the original conservation state, see Figure 4 for reference.

Since the tape has a known emissivity, which is equal to 0.96, it is possible to evaluate the emissivity of the marble by means of a comparison. In detail, by comparing the temperature values measured by the thermal camera of the tape and of the contiguous undamaged marble, it has been evaluated that the original emissivity of the marble is equal to 0.91. This value represents the reference emissivity related to the original conservation state of the bust. The deterioration state of the sculpture parts having material alterations can be assessed by comparing the emissivity changes. In [19], the authors have defined a new colour palette to highlight the emissivity variations. The temperature range of the image has been subdivided into sub-ranges to perform a classification. Ten uniform classes have been considered assigning a colour from black to white as in Figure 5.

Figure 4. Evaluation of the original emissivity of the marble.

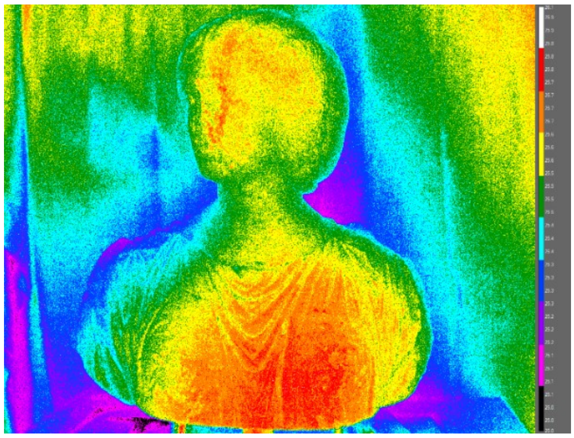

Figure 5. Emissivity changes due to material alteration.

The central class having a light blue colour (fifth class) in Figure 5 depicts the undamaged areas of the sculpture having the original emissivity. A look at Figure 5 permits an overview of the damaged parts of the sculpture having a different emissivity. Different colours highlight parts of the sculpture with material alterations and consequent emissivity changes. As a consequence, this figure provides qualitative information on the sculpture's deterioration state. Analysis in [18], shows 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 material alterations (deposition of iron oxide, alveolisation and damages).

3. EXPERIMENTAL RESULTS

Previous results, obtained by using passive thermography, provide relevant information to characterize emissivity changes. However, such results do not allow user to distinguish the specific material alteration which is a cause of the emissivity variation. For this reason, active thermography is here proposed to characterize the dynamic response of the bust to external thermal solicitation. This response provides complementary information and can be used to characterize the specific material alteration. The aim of the present study is to provide an innovative technique to characterize processes of alveolisation or deposition of iron oxide.

To this aim, an IR lamp has been used, see Figure 6 for reference. The bust surface has been heated up for 7 seconds to provide a sufficient temperature gradient. The thermal response

Figure 6. IR lamp.

Figure 7. The chosen three circular ROIs (from bottom): Iron Oxide (in brown colour); alveolisation (in blue colour); pure marble (in green colour).

has been recorded for about 30 seconds. Three ROIs have been chosen to compare the marble thermal response. Figure 7 reports the circular ROIs referring to three different parts of the sculpture: 1) a portion with deposition of iron oxide (in brown colour); 2) a portion affected by alveolarisation (in blue colour); 3) a portion of the marble having its original conservation state (in green colour).

The temporal trend of the thermal response of each ROI is reported in Figure 8. Starting from the bottom of Figure 8, it is possible to see the response of a part of the bust with traces of iron oxide; the trend in the middle represents the thermal response of a part of the bust affected by alveolisation process; the upper line reports the temporal trend of a part of the sculpture maintaining its original state of pure marble. By a look to the plot, it is easy to observe a different response of the three parts due to the material alteration. By means of experimental data, the authors can assert that deposits of iron oxide are cause of temperature changes included in the range [0.38 0.42]. Instead, alveolisation process is cause of temperature changes in the interval [0.08 0.1]. Further similar analyses have been carried out in other parts of the bust obtaining results which are compliant with such data. By considering the emissivity value of the pure marble without material alteration and its temperature value as references, it is possible to characterize the parts of the sculpture belonging to one of the chosen categories: pure marble; alveolised marble and iron oxidized marble. It is opportune to clarify that the bust characterization is still in progress, therefore other material alterations are currently under analysis. However, the authors aim to report the preliminary results of their experimentation to show the potentialities of the proposed methodology. So a new colour palette has been defined to highlight the parts of the sculpture belonging to one of the three investigated cases. In detail, green colour highlights the pure marble parts of the bust without any material alteration. Blue colour depicts the parts affected by alveolisation process. Bown colour shows up the parts having traces of iron oxidation. And finally, black colour has been associated to other parts of the image which are not belonging to the previous considered cases. Figure 9 reports the results of the proposed classifications. The image shows clearly the parts of the bust associated to the three categories. Most of the sculpture surface is coloured black, such parts are realistically affected by erosions, damages, defects, fissures and material irregularities. Although such data include only partial results of the experimentation, the authors think that this methodology could open new features of thermography application to archaeology field.

Future work will be aimed to overcome the issue concerning the non-flatness of the surface by recreating a 3D thermographic model of the sculpture so reducing possible errors of the classification.

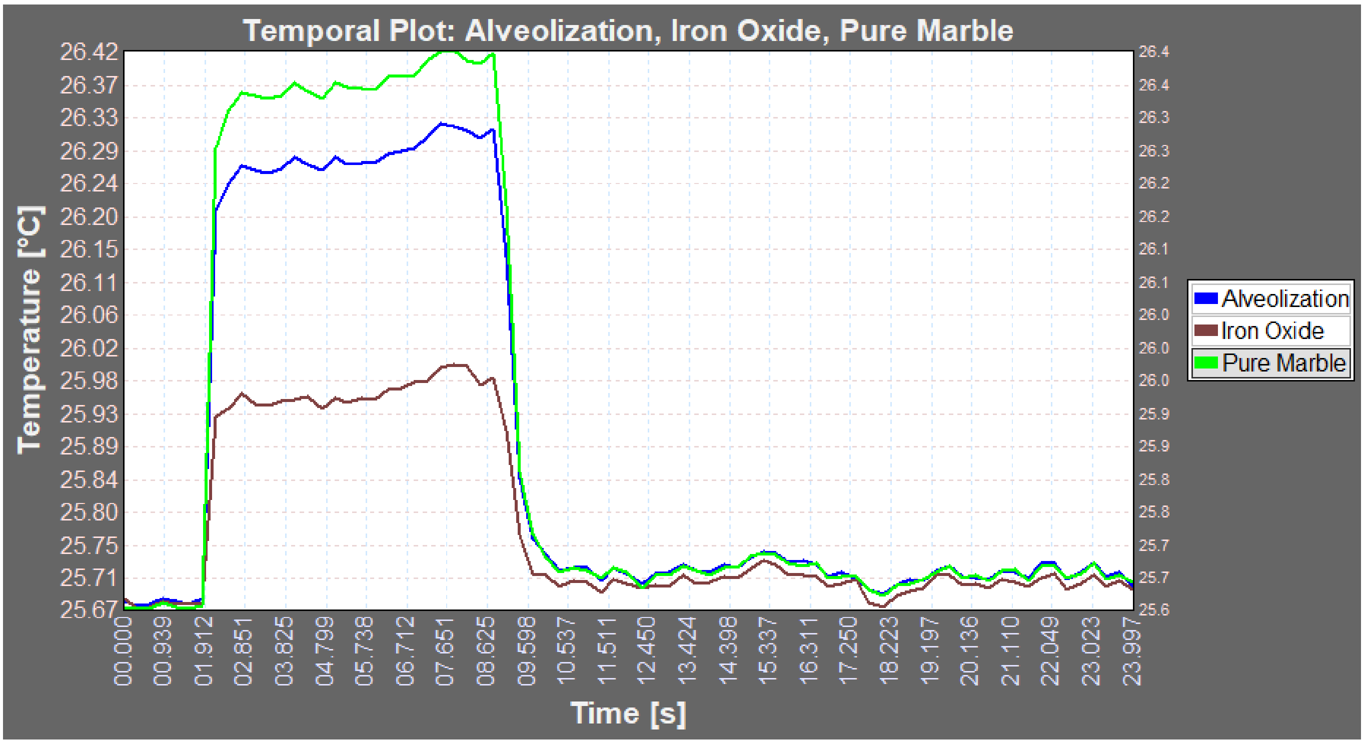

Figure 8. Plot of the thermal response of the three ROIs over time (from bottom): Iron Oxide (in brown colour); alveolisation (in blue colour); pure marble (in green colour).

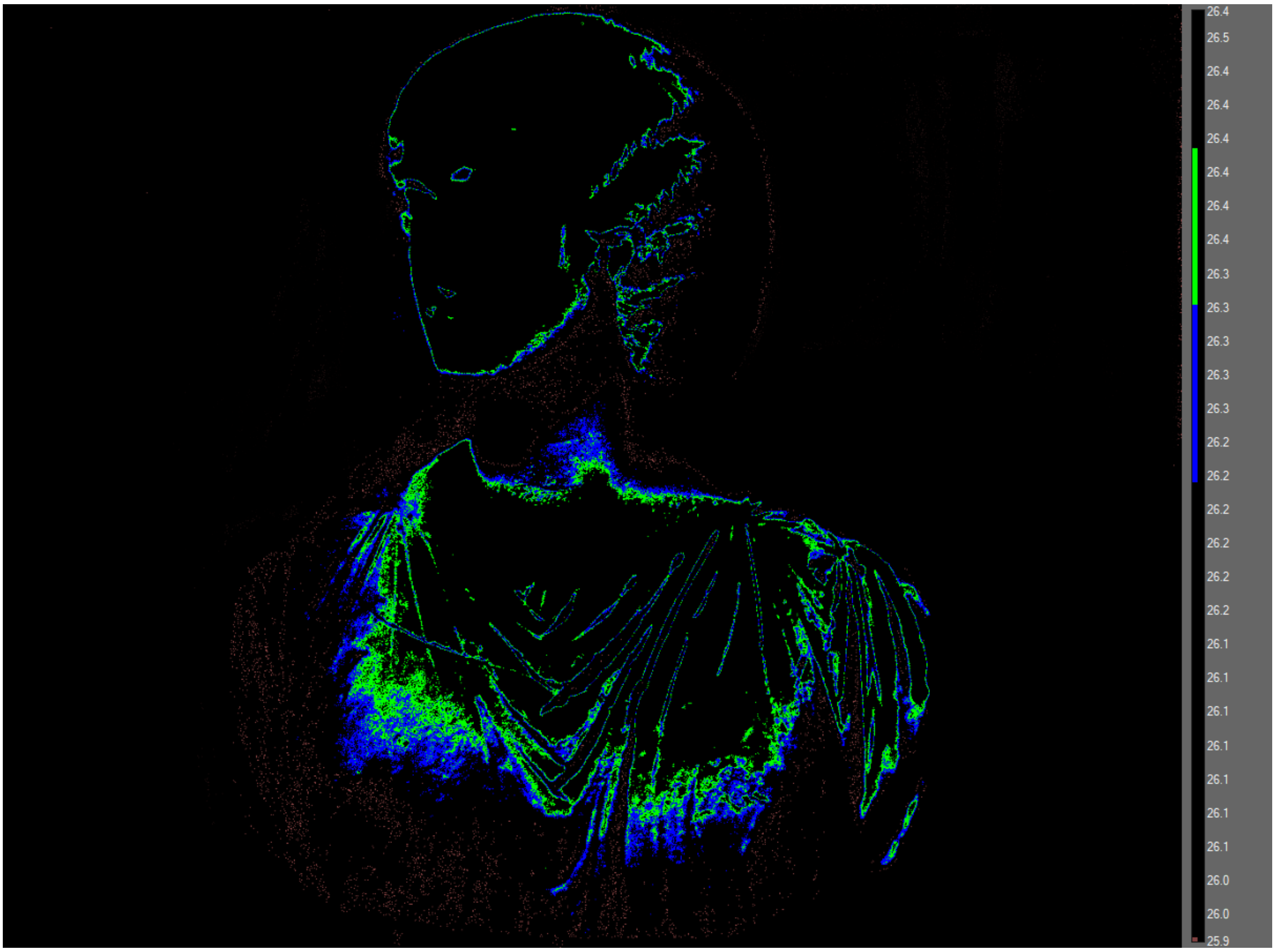

Figure 9. Classification of material alterations: pure marble (green colour); alveolised marble (blue colour); iron oxidized marble (brown colour).

4. CONCLUSIONS

This paper reports the preliminary results concerning an innovative use of thermography to characterize material alterations in archaeological findings. The proposed technique has been applied to evaluate the conservation and degradation state of a marble bust of ancient Rome of Crispina, the wife of the emperor Commodus (180-187 A.D.). The sculpture is preserved at the Archaeological Superintendence of Reggio Calabria, Italy. The methodology uses emissivity changes in order to characterize different degradation states as well as alveolisation, erosion, damages, and deposition of iron oxide. Experimental data have shown that changes in emissivity, with respect to the original value, can be used to highlight material alterations. Although the present results take into account only the effects of alveolisation process and iron oxide deposition, they offer interesting and challenging perspectives about the potentialities of thermography in characterizing material degradations and alterations. In fact, emissivity changes are caused by apparent changes in surface temperature even if the object is in thermal equilibrium. This effect is clearly visible in the thermographic images by means of different colour shades.

Passive and active thermography has been used to evaluate the static and dynamic thermal properties of the sculpture. The original emissivity and equilibrium temperature have been estimated and assumed as reference values. An IR lamp has been used to analyse the thermal response of the bust. Any temperature deviation from the reference value has been measured and characterized to correlate the change to a specific material alteration (alveolisation and iron oxide deposition).

Results have shown the effectiveness of the proposed methodology. Qualitative and quantitative information provides an overview of the total deterioration state of the discovery. Future work aims to complete the characterization of other degradation and alteration processes as well as erosion, damages, defects, fissures and material irregularities. Currently, experimentation is still in progress, however, preliminary results show that thermography can be considered an effective diagnostic tool for evaluating the conservation state of archaeological findings offering new instrumental methods to assist operators during the restoration process.

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