

The Heritage Building Information Modelling System for non-destructive optical techniques: The case study of the restoration of a Marble sculpture on the façade of the Gesù Nuovo Church in Naples

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ABSTRACT

The study focuses on an angel marble sculpture, placed on the central portal of the Gesù Nuovo church in Naples. The non-destructive and non-invasive optical techniques used were Active Thermography (AT), Colorimetry and 3D scanning. The measurements were carried out before and after the restoration of the marble sculpture, consisting in the consolidation of some disintegrated areas and in the removal of both black crusts and biodeteriogens, present in various areas of the sculpture. AT images provided a map of the structural inhomogeneities of the investigated areas, measuring the thermal response. 3D scanning, on the other hand, provided a 3D model of the entire sculpture and measured on a millimeter scale any structural variations due to the restoration. Lastly, colorimetry allowed a quantitative measurement relating to the color variation of the surface of the sculpture due the cleaning process. All this information was collected and entered into the HBIM (Heritage Building Information Modelling) system, which allowed a systematic cataloguing, providing a complete database on the made measurements.

Section: RESEARCH PAPER

Keywords: active thermography; HBIM; 3D scanning; marble sculpture; non-invasive optical diagnostics

Citation: Ch. Saltarelli, M. Rippa, V. Pagliarulo, M. R. Vigorito, M. Paturzo, The Heritage Building Information Modelling System for optical non-destructive techniques: The case study of the restoration of a Marble sculpture on the façade of the Gesù Nuovo Church in Naples, Acta IMEKO, vol. 14 (2025) no. 1, pp. 1-8. DOI: [10.21014/actaimeko.v14i1.1815](https://doi.org/10.21014/actaimeko.v14i1.1815)

Section Editor: Fabio Leccese, Università Degli Studi Roma Tre, Rome, Italy

Received February 27, 2024; **In final form** March 10, 2025; **Published** March 2025

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1. INTRODUCTION

In this case study, the HBIM system [1], which consists in the construction of an information system for historical heritage using the Edificius program of Acca software, was tested integrating the data obtained by means of the performed optical NDT (non-destructive testing). The latter has proved to be particularly useful, in the field of restoration, for the planning of the intervention, monitoring and subsequent use of the artefact [2]. Therefore, optical NDT techniques have now become a common practice in the preliminary stages of restoration.

The HBIM system consists of a model plus a platform, ACDat (Data Sharing Environment) where all the information is collected in ordered folders and can be linked directly to the 3D modelling on the platform usBIM (BIM Management System). The model becomes a graphic support for the analysis and

documentation of the work, for the preservation of the digital copy, the localization of heterogeneous information and allows a faster dialogue between the different specialists who collaborate in the restoration process. The case study deals with an experimental restoration using products that are non-toxic to the operator and have a low environmental impact. The diagnostics were used both to know in detail the degradations present, so as to be able to make the most of the potential of sustainable products, and to confirm their effectiveness. From this point of view, the system could be very useful as a database to see, years later, how these products have changed and what relationship they have acquired with the work of art. The HBIM system was tested to integrate the data acquired on a 17th century marble sculpture investigated through the use of three non-destructive optical techniques (NDT): active thermography (AT), colorimetry and 3D scanning. These techniques have never been

tried all at once. There are many cases where thermography has been coupled with colorimetry to see the effects of cleaning on wall paintings in very humid environments [3]. In other cases, thermography was coupled with 3D scanning to monitor physical damage on wall paintings [4].

AT is a well-known non-invasive imaging technique increasingly applied to study samples of interest for cultural heritage [5]-[13]. In particular, on marble sculptures it is used to highlight iron pins and stress or thermal shock. According to this technique, the investigated work of art is stimulated by external heating and its thermal response is recorded through the use of an appropriate infrared camera. As a result, any type of anomaly that determines a variation in the thermo-physical properties of the sample under examination can be efficiently detected.

The colorimetry allows to quantify and describe physically the human colour perception. It is based on the use of standardised numerical models and parameters and allows to compare the chromatic characteristics of pigments before and after a restoration work, quantitatively determining the effectiveness of the recovery procedure implemented [14]-[17]. Structured light 3D scanning captures objects quickly and accurately: structured light is a calibrated grid of white or blue light projects onto the object while it is scanning [18]. Usually, this grid is a series of parallel and criss-crossing lines. When structured light hits the object, the light grid is distorted by curves, depressions, or raised areas of the surface. Meanwhile, the scanner's camera captures these distorted light patterns frame by frame, while the scanning software analyses the grid and uses it to accurately reconstruct all surfaces of the scanned object in digital 3D. This technology finds valuable applications in different research fields, ranging from orthopaedics to virtual museums [19]-[23]. Using 3D scanning to support diagnostics during restoration works presents some benefits, starting from the feasibility of the measurements. In our case, in fact, the scaffolding erected for the restoration work was an obstacle to a good photogrammetric shot. Therefore, using 3D portable scanner allows greater freedom and immediacy of the result. Immediate comparison of the data on the platform between the measured areas and the post-restoration interventions. The monitoring would be much easier for the diagnostician having a supported database of photos that sees how over time there are variations in the measurements compared with the areas of the object.

2. MATERIALS AND METHODS

2.1. Marble sculpture analysed and implemented restoration procedure

The sculpture is located to the right of the central portal of the church of Gesù Nuovo of Naples, the result of superimpositions by Tuscan artists towards the end of the 17th century. The sculpture is composed of white marble, most likely from Carrara, given the nationality of the artisans, and was certainly made from a single block; its total dimensions are 210 cm long and about 165 cm high. The work is part of a rather complicated context: the façade of the church has been exposed for years to a particularly busy area. This condition caused a lot of atmospheric particulate matter to attack the stone substrate of the marble decorations. In fact, the sculpture had widespread black crusts (dendritic) and a widespread biological attack due to neighbouring plants and bird droppings. The causes are to be linked to the eroded matrix of the stone due to acid rain, which is inevitable in the outdoor environment. The restoration of the sculpture, lasting eleven months, was carried out in an almost

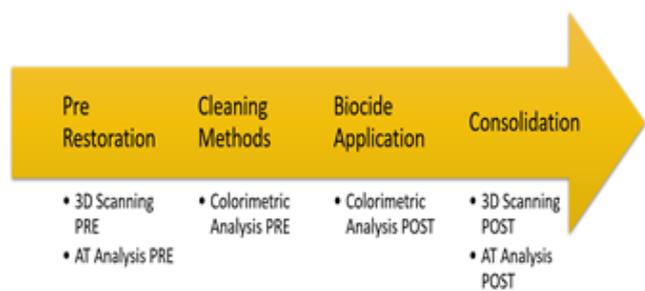


Figure 1. Timeline of the restoration work and measurements carried out.

totally sustainable way, with few toxic products for humans and the environment, respecting the criterion of minimum intervention. In particular, the cleaning was carried out with only sodium bicarbonate and Agar-agar gel. The other operations, related to the non-destructive diagnostic analysis, concerned the consolidation, cleaning and use of an essential oil-based biocide. In pre-consolidation, water based 30 % nanosilica was used. In addition, a natural biocide based on three essential oils has been tested by comparing its effectiveness with a traditional biocide whose results are well known. The success of this methodology, compared to the "traditional" one, used for the rest of the marble compositions, has given excellent final results and the confirmation has also been given by diagnostic analyses (Figure 1).

2.2. Active Thermography setup

Active Thermography (AT) measurements were made in situ both before and after the restoration work on the marble sculpture. A portable hot air generator was used to thermally stimulate the investigated area of the statue. Due to its location (next to a wall and between support structures), not all areas of the statue were accessible for investigation. We analysed in total 8 areas of the statue (shown in green squares in Figure 2) with size between about $25 \times 25 \text{ cm}^2$ and $45 \times 45 \text{ cm}^2$. During the heating, the temperature of the surface was monitored to achieve a maximum $\Delta T = (7 \pm 1) \text{ }^\circ\text{C}$ as uniform as possible on the area stimulated. The thermal response obtained during and after heating was recorded with a frame rate of 10 Hz using the LWIR camera AVIO TVS500 (spectral range 8–14 μm , FPA 320×240 pixels, NETD $0.05 \text{ }^\circ\text{C}$) mounting a 11 mm focal lens. The commercial IRT Analyzer (GRAYESS) software, with which the camera is supplied, was used for real-time temperature monitoring and management of the basic camera parameters. The average emissivity of the surface of the sculpture was evaluated both before and after the restoration work using opaque black reference tape with known emissivity (0.95) and the estimated values of 0.92 (before restoration) and 0.86 (after restoration) were considered in the analysis. The measurements were carried out under environmental conditions with a temperature in the range 17–21 $^\circ\text{C}$ and humidity in the range 51–55 % rH for both PRE and POST restoration analysis.

2.3. Colorimetric analysis

Colorimetric analyses were carried out by light absorption in diffuse reflection using a MAYA 2000 pro (Ocean Insight, Oxford, UK) spectrophotometer in a Pump-Probe configuration. A probe with a core diameter of 1 mm was used for the measurements. A halogen lamp (CIE standard illuminant D65, Ocean Insight, Oxford, UK) with an emission spectrum in the VIS-NIR range 400–1000 nm was used as a light source. The device was calibrated using a white ceramic disk and a black

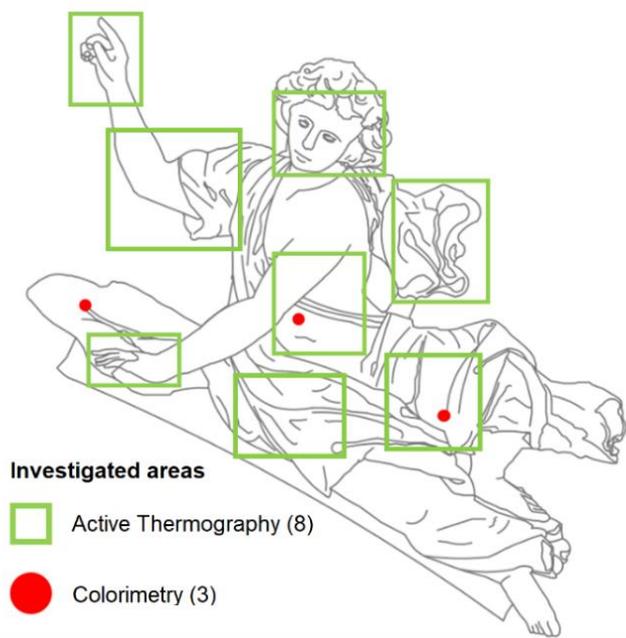


Figure 2. Mapping of the areas investigated on the statue by the use of Active Thermography (green squares) and colorimetric analysis (red circles).

trap portion. The software OceanView 2.0 (Ocean Insight, Oxford, UK), was used for the acquisition of the colorimetric data, the reflected spectra and for basic operations. Colorimetric parameters were calculated in the CIE $L^* a^* b^*$ 1976 colour space. In this system, L^* coordinate is lightness, a^* coordinate represents the green/red component, and the b^* coordinate refers to the blue/yellow component. The measurements were conducted before and after the applications of biocidal products on three different area of the statue of about 3 cm^2 : on drapery, base and torso of the marble sculpture (red circles in Figure 2). In each area considered, 10 measurements were carried out at different points, the results achieved were averaged and the standard deviation calculated. The area of the torso showing the original colour (marble white) was taken as reference.

2.4. 3D Scanning measurements

To validate the success of the consolidation products used, in particular water based nanosilica and lime water, it was decided to make a 3D scan of the statue's right arm. In fact, the right arm was more degraded than the rest of the statue and was an excellent area to test the effectiveness of these products. We use 3D scanning techniques, opting for structured-light scanning, a non-invasive contactless method that infers an unknown 3D geometry of a surface based on the distortion of known projected light patterns. This technique is rapid and allows to assess sculpture 3D geometry in situ. For the 3D scanning phase, the Artec Eva handheld structured-light 3D scanner, which records both object geometry and texture, was chosen as the recording tool.

It uses white structured light and camera (1.3 MP), has an accuracy of 0.1 mm and a maximum point resolution of 0.2 mm. The scanning is followed by a post-processing of the gathered data, using a dedicated software (Artec Studio 17). The scanner is very easy to use as it is portable. The right arm was scanned prior to the application of any product: it took three continuous scans and four the second time at the end of the restoration. During this process the separate scans are cleaned and aligned to obtain the full 3D geometry of the sculpture.

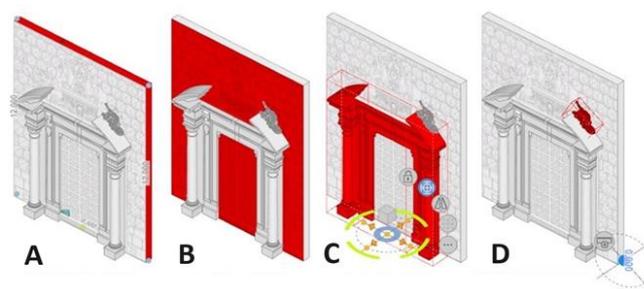


Figure 3. Inclusion in Edificius: The various elements have been inserted in different formats: AB) the ashlar, which characterises the façade, has been inserted as a texture/orthophoto applied to the *Involucro* object; C) the portal was made in CAD as an ideal model and D) the sculpture was imported as a reality-based model, textured photogrammetric mesh.

2.5. HBIM implementation

Only the areas of the façade of interest have been broken down and modelled: the central portal and the sculpture that is the subject of the study, reasoning by semantic deconstruction (Figure 3). The 3D model of the entire sculpture was made using digital photogrammetry. The photogrammetry technique makes it possible to identify the spatial composition of all points on the object. It is a surveying technique that allows important information about physical objects and the environment to be obtained through the process of recording, interpreting and measuring photographic images. This sculpture was processed using the photogrammetry software developed by 3Dflow to reconstruct 3D models from photographs, 3DF Zephyr [24]. The photographic images were taken with a mobile phone: Oneplus 5T, 16-megapixel camera with a resolution of 4638×3436 pixels and thanks to the use of markers. Six markers were used and placed on the mortar base of the sculpture (two on the front and two on the back, one on the right and one on the left) placed 35 cm apart. Thanks to the orthophotos elaborated by the photogrammetric model, it was possible to elaborate the various thematic mappings, necessary for the documentation of the work and to support the restoration activities. In addition, a unified visibility of the sculpture, lost with the presence of the scaffolding, was recovered (Figure 4).

3. RESULT AND DISCUSSION

3.1. AT analysis

The AT analysis was performed on the marble sculpture investigated before (PRE) and after (POST) a planned restoration work. The main objective of these analyses was to detect the presence of anomalies affecting the sculpture, the causes that determine them and their spatial distribution to obtain both a visual and quantitative description relating to its state of conservation by carrying out monitoring over time. PRE-restoration measurements allowed to detect the presence of crusts, thin biological patinas and some structural anomalies which affected different areas of the sculpture, mostly not visible to the naked eye. According to this information, a targeted and specific action was implemented in the restoration works to remove these contaminants and anomalies. The results of this work were then analysed by POST-restoration measurements comparing the latter with the thermal data acquired in the PRE-restoration analysis.

As an example, Figure 5a shows the visible and thermal images obtained both in the PRE and POST phase of one of the



Figure 4. Textured photogrammetric mesh and the photo of the sculpture on the construction site.

analysed areas of the sculpture referring to the body. The thermal image refers to the induced thermal gap ΔT measured 50 s after an external stimulation heating and achieved by subtracting the thermal frames $\Delta T = T(t = 50) - T(t = 0)$ extrapolated from the recorded sequences $T(t)$. As visible from the images, the average ΔT referring to the inspected area obtained in the PRE-phase is about 4 °C and therefore almost double compared to that measured in the POST-phase of about 2.2 °C.

It is interesting to note, the difference in ΔT is relevant not only in the area affected by a black crust (well evident in the visible pre-restoration image) but also in all the surrounding surface. The latter is due to the presence in the PRE-restoration phase of a thin contaminating patina which affected most of the inspected surface, not visible to the naked eye but detectable by the thermal analysis carried out.

Figure 5b shows the temporal thermal trend extrapolated in the PRE- and POST-restoration analysis of the P1 region (indicated in thermal images in Figure 5a referring to an area of the surface of the sculpture where no crusts or contamination are visible to the naked eye). As can be seen, the PRE-trend (black line) shows a slower thermal recovery than the POST-trend (red line) as an effect of the presence of the contaminating patina eliminated during the restoration works.

In general, the presence of crusts and patinas on the surface of the sculpture modifies both its optical and thermal properties. From a thermal point of view, the presence of contamination increases the roughness of the surface and this, as measured during our PRE and POST investigations, induces an increase in the average emissivity (0.92 pre-restoration and 0.86 post-restoration) relating to the surface of the sculpture. From an optical point of view, this increase induces a reduction in reflectivity and the consequent increase in absorption of the

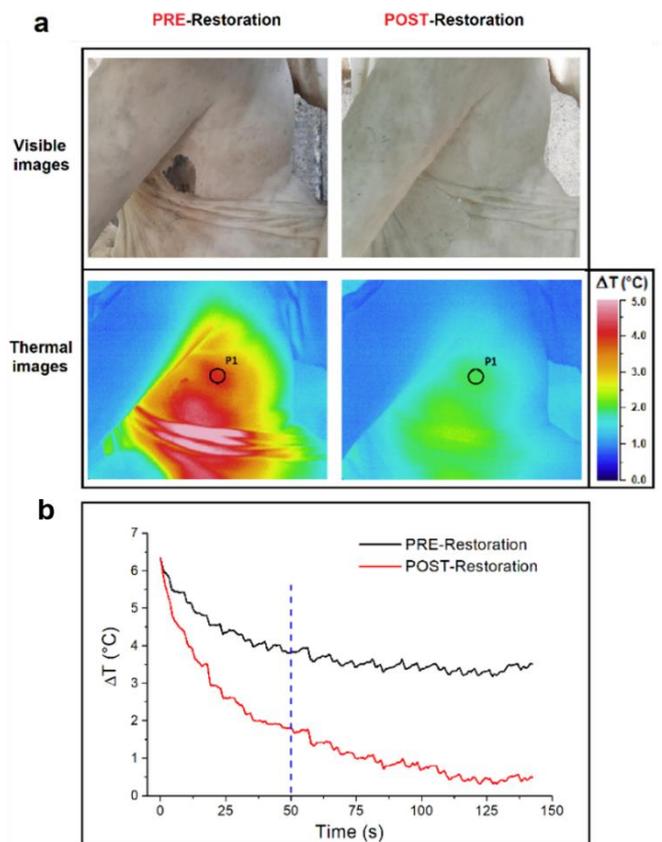


Figure 5. Example of AT analysis carried out on an investigated area of the marble sculpture: a) thermal and visible images acquired before (PRE) and after (POST) the restoration work, b) PRE (black line) and POST (red line) temporal thermal trend of the area P1.

visible solar spectrum. Consequently, the contaminated surfaces of the sculpture are affected by both a greater overheating during the daily cycle (especially in the hottest hours) and a slower heat dissipation. Basically, the presence of such crusts and patina on the sculpture can lead over time to serious problems of degradation and deterioration due to the greater thermal stresses affecting these areas. Figure 6 shows the AT analysis referring to the hand of the sculpture.

As can be seen, the PRE-restoration measurements highlight how the fracture visible on the hand delimits two areas with very different thermal responses. This was presumably due to the presence of a subsurface void (cavity) into which air, humidity and rainwater entered through the crack. Their accumulation under the hand increased the thermal inertia and slowed down the natural process of heat dissipation. The comparison between the PRE and POST thermal images shows how this discrepancy in the thermal behaviour of the two parts of the hand was greatly attenuated after the local filling carried out during the restoration works.

Figure 6b shows the spatial temperature profiles referred to the P1 lines indicated in the thermal images in Figure 6a. The comparison of the PRE (black line) and POST (red line) measurements also confirms from a quantitative point of view how the two parts of the hand show a much more similar thermal response after the restoration intervention. It should be noted that in both examples shown the thermal differences found in the PRE and POST-restoration analyses are well above the Noise Equivalent Temperature Difference (NETD) of the infrared camera used of 0.05 °C and therefore can be considered

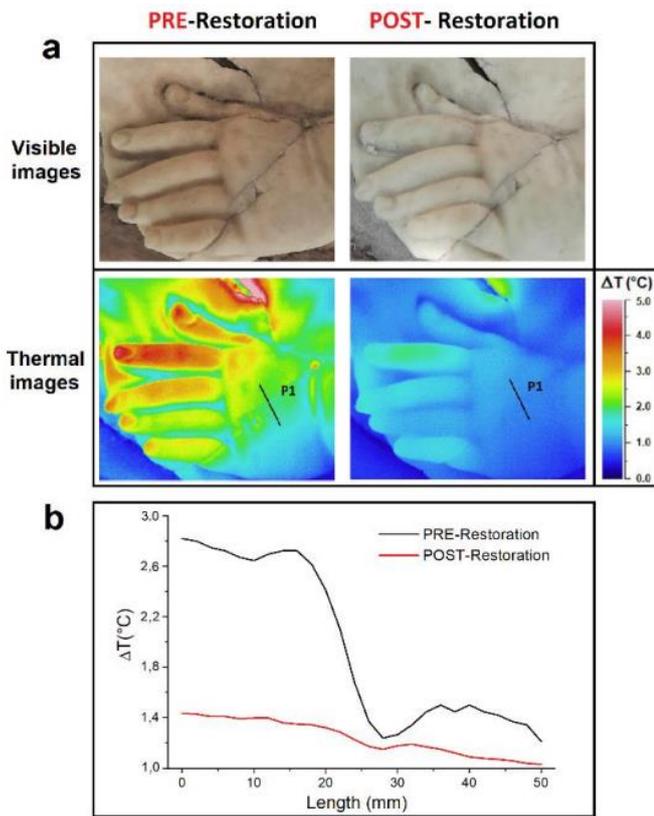


Figure 6. AT analysis of the hand of the marble sculpture investigated: a) thermal and visible images acquired before (PRE) and after (POST) the restoration work, b) PRE (black line) and POST (red line) spatial temperature profiles referred to the P1 lines indicated in the PRE and POST thermal images.

significant. The examples reported here represent a synthesis of the analyses and results obtained with the AT technique, they highlight the important role that this method can play in the inspection of sculptures similar to those investigated: 1) in the pre-restoration phase to detect anomalies not visible to the naked eye and provide important information to carry out targeted interventions and 2) in the post-restoration phase to evaluate the effectiveness of the interventions implemented and detect any persistent problems.

3.2. Colorimetric analysis

The colorimetric analysis was conducted on three areas of the sculpture and the parameters CIE $L^*a^*b^*$ detected on them were compared before and after the restoration work. Table 1 shows the difference between the parameters measured before and after the restoration work for two areas of the sculpture A1 (drapery) and A2 (base) affected by thin biological patinas and treated with the procedure described in section 2.3 and a reference area A0 (torso) not affected by contamination and untreated.

Table 1. Difference between the $L^*a^*b^*$ parameters (dimensionless units) measured before (PRE) and after (POST) the restoration work for two treated areas of the sculpture A1 and A2 and a reference untreated area A0.

Area	PRE-restoration			POST-restoration		
	$ \Delta L^* $	$ \Delta a^* $	$ \Delta b^* $	$ \Delta L^* $	$ \Delta a^* $	$ \Delta b^* $
A1-A0	22 ± 3	4.18 ± 0.06	11.87 ± 0.07	2 ± 1	2.04 ± 0.05	7.81 ± 0.07
A2-A0	23 ± 2	3.10 ± 0.04	9.83 ± 0.06	4 ± 2	1.14 ± 0.05	6.36 ± 0.04

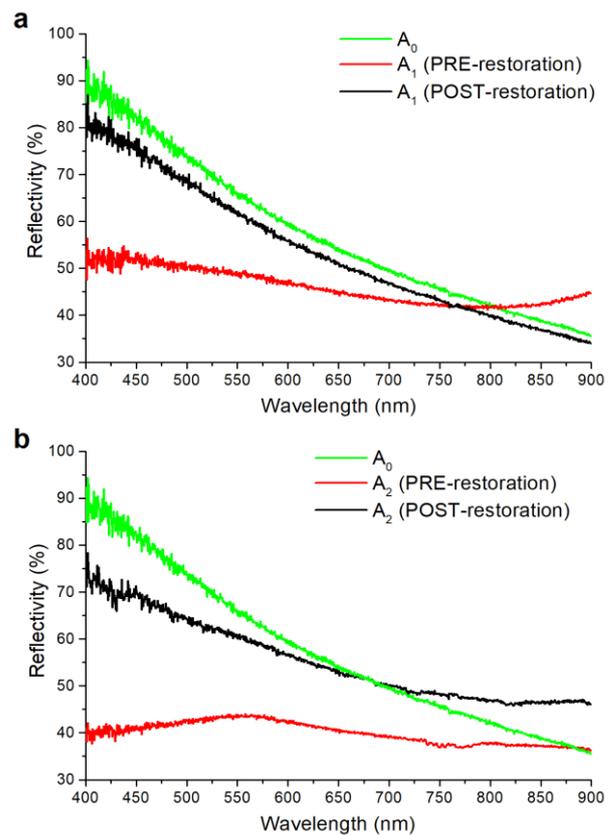


Figure 7. Reflectivity spectra measured on areas A1 (a) and A2 (b) PRE- (red lines) and POST-restoration (black lines) are reported and compared with that of the reference area A0 (green lines).

As can be seen by comparing the values obtained PRE- and POST-restoration, for both treated areas A1 and A2 all three parameters ΔL^* , Δa^* and Δb^* were reduced after cleaning, indicating a drift of the colour of these areas towards that of reference A0. Considering the standard deviations reported for each measurement, the comparison of results achieved before and after restoration show a clear non-overlap of the confidence intervals confirming as the variations of the parameters measured can be considered statistically significant. In Figure 7, the reflectivity spectra measured on areas A1 (Figure 7a) and A2 (Figure 7b) before (red lines) and after (black lines) the restoration work are reported and compared with that of the reference area A0 (green lines). As visible from the reflectivity spectra, the curves of A1 and A2 measured PRE-restoration are very different from that of A0 but both shift towards the latter in POST-restoration measurements. The POST spectrum referred to A1 better matches that of A0 than the POST spectrum measured for A2. Therefore, this analysis gave an indication regarding the results obtained from a colorimetric point of view through the restoration work, highlighting the areas of the sculpture where the cleaning intervention carried out was totally or only partially successful.

3.3. 3D Scanning results and insertion into the usBIM platform

Thanks to the 3D scanning of the sculpture arm which, as mentioned above, showed a more advanced disintegration than the rest of the composition, it was possible to quantify the result of the consolidating effect given by the nanosilica basis and the lime water (Figure 8). It results that the restoration work has not



Figure 8. Results obtained from the 3D scanning that took place before and POST restoration inserted in the usBIM platform.

caused structural changes, but only a decrease in the surface roughness in some parts of the marble sculpture, i.e. the marble surface after the restoration work appears more compact and smoother. In Figure 8 it is possible to see and compare the success of the intervention directly on the platform.

In Figure 9 the 3D tag is directly linked to the degradation marker; the diagnostician can see the degradation area and at the same time decipher the result even during data processing. The goal is to make the most of the possibilities of this software and the sharing system to facilitate diagnostics as well. This method of online sharing not only allows you to have a digital bank where you can compare the results of the before and after restoration, but also a bank for the monitoring campaign. The ACDat can be structured in accordance with the proposed workflow.

3.4. Final achievement: Data sharing with HBIM

All the shots taken can be entered into the usBIM platform of Acca Software which allows the sharing of the project. In this way, the diagnostician, together with the restorer, can share the results in real time on the model and the restorer can give more detailed explanations to the operator. In the case of thermography, it is possible to discuss the possible causes that led to an abnormal thermal behaviour: as in our case on the angel face which had a veil of black crusts that changed the behaviour of the material (Figure 10).

Thanks to the marker it is possible to associate to the object (Sculpture) all the various photos taken by the restorer and the

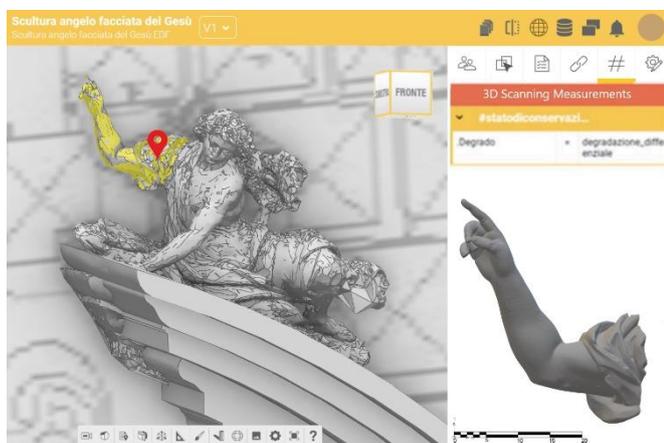


Figure 9. Scanning of the 3D model on the platform, also tagged to the type of degradation affecting the area and the intervention carried out.

diagnostician on the same area attach the results of the measurements. The software makes it possible to bring together different information from different operators. Since the model is online, it is possible to share it via links to all interested parties. In this way, communication between the various professionals is much easier and there is instant feedback. As we will see, the diagnostician can compare the results and process them with the help of the information uploaded by the restorer on the type of degradation or intervention. As anticipated, colorimetry was tested on two points treated by a different biocide: in part 1, biocide based on three essential oils and in part 2, Benzalkonium Chloride (Figure 11). The two markers on the two differently

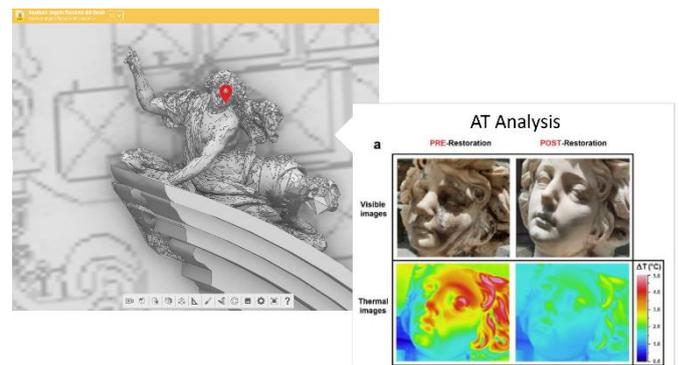


Figure 10. Sharing of the results of the thermographic analysis on the face of the sculpture on the usBIM platform.

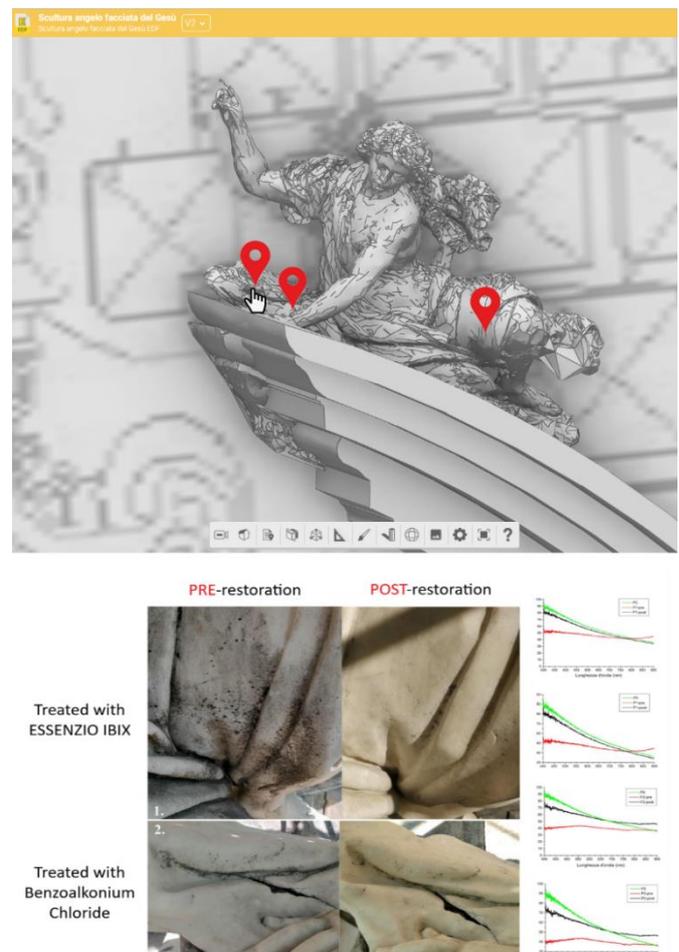


Figure 11. Sharing the two Colorimetric analysis results in two different markers.

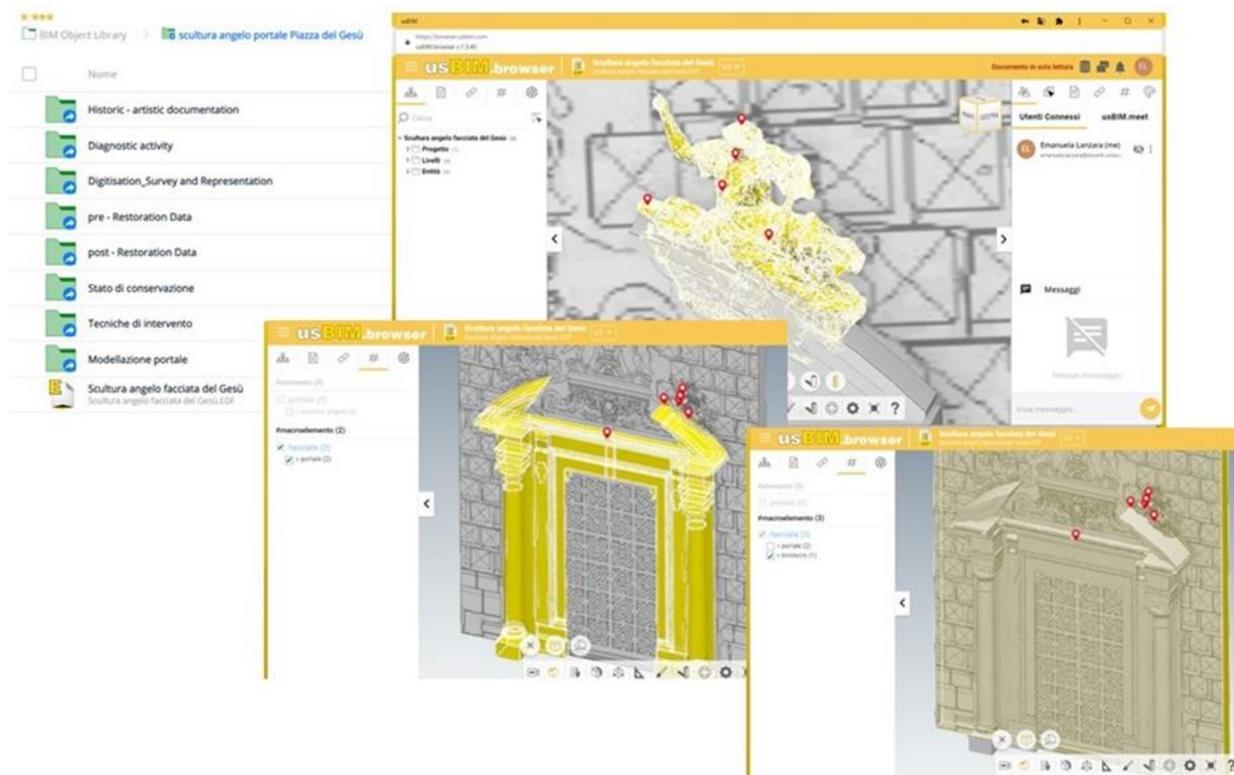


Figure 12. Layout of the program with all the markers, links and tags inserted in the template and the folders where it is possible to find the information individually.

treated areas can either contain the same type of information for a more immediate comparison or treat them separately. They can also be used in total autonomy by dividing them into subcategories. The information contained can also be subdivided and subcategories created. The organisation and geolocation of the information facilitate the search for the degradation information detected, NDT diagnostics and minimally invasive. The query of the system on the platform through markers, #tag and links facilitate the sharing of data and enriches the model with specific information referring to the work, the context and the operations carried out (Figure 12).

4. CONCLUSIONS

We exploited three non-destructive and non-invasive imaging techniques, i.e. Active Thermography (AT), Colorimetry and 3D scanning, to support the restoration work of an angel marble sculpture, placed on the central portal of the Gesù Nuovo church in Naples. The measurements were carried out before and after the restoration of the marble sculpture, consisting in the consolidation of some damaged areas and in the removal of both black crusts and biodeteriogens present in various areas of the sculpture. It results that the restoration work has reduced the structural in-homogeneities, making the marble surface more uniform and smoother, and therefore more resistant to external mechanical and thermal stress. All this information was collected and entered into the HBIM system, which allowed a systematic cataloguing, providing a complete database on the made measurement. The use of HBIM offers the possibility to correlate heterogeneous information (architectural, material and also historical information) with their spatial referencing, therefore enabling better decision-making about heritage maintenance and management.

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