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Documenting the State of Preservation of Historical Stone Sculptures in Three Dimensions with Digital Tools

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Abstract. Protection of stone heritage requires detailed records of the state-of-preservation to ensure accurate decision-making for conservation interventions. This short paper explores the topic of using digital tools to better visualize and map in three-dimensional (3D) representations the deterioration state of stone statues. Technical photography, geomatics techniques, and 3D visualization approaches are combined to propose reproducible and adaptable solutions that can support the investigation of historical materials' degradation. The short paper reports on the application of these multi-technique approaches regarding a bust sculpture from the *Accademia Carrara* in Bergamo (Italy).

Keywords: Spectral Imaging, Structured Light Scanning, Photogrammetry, 3D Visualization, Decay Mapping, Stone Heritage

1 Introduction

A significant part of our tangible heritage is made of stone and continually undergoes decay, which creates significant challenges for ensuring its preservation over time [1]. Stone is subjected to degradation mechanisms, which can be caused by external or internal factors [2]. The exposure to external environments triggers various degradation phenomena, leading to the decay of the stone matrix, resulting in loss of the original details and colors [3]. Detailed analysis and monitoring of deterioration patterns can contribute to the knowledge of the degradation mechanisms and effectively assist the decision-making process regarding necessary conservation interventions.

Traditional approaches for evaluating and representing the preservation state for stone statues involve visual inspection and analog two-dimensional (2D) sketching of deterioration maps. Nevertheless, the stone degradation's exhaustive characterization requires time-consuming multi-technique diagnostical campaigns with spectroscopic and chemical methods, including non-invasive and invasive analyses [4,5]. However, the heightened interest in ensuring the sustainability of stone heritage on a broad scale dictates the design and implementation of cost-effective, flexible—and relatively automatic—workflows for assessing and visualizing the state of conservation. Towards this direction, geomatics can provide useful solutions by offering digital tools

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for agile geometric and radiometric recording and 3D processing of the documented data that can help understand heritage objects' condition.

Recent technological advancements have enabled the acquisition of suitable and rich data for cultural heritage documentation. Photogrammetric recording approaches employing structure-from-motion (SfM) algorithms have become quite common for heritage studies due to their capability of restituting 3D geometry from oblique imagery, estimating the camera's geometry without the need for predefined sets of control points or prior calibration, and due to the reduced needs for supervision and user-expertise [6,7]. Semi-automated workflows combining SfM, dense multi-view reconstruction (DMVR), and 3D meshing algorithms have been frequently applied to record the condition of stone sculptures and high reliefs for conservation purposes [8,9] and to support interventions through virtual restoration and 3D printing of missing parts [10–12]. Also, Structured-Light Scanning (SLS) has significant advantages for implementing stone heritage documentation. SLS systems are easy to use, compact, lightweight, and provide dense resolution and high accuracy results [6,13,14]. However, the approaches mentioned above frequently focus only on the 3D shape of stone heritage and the volume of material loss but do not examine the deterioration patterns. To faithfully represent degraded surface microstructure, different shading and rendering techniques can be adopted for the digital models [15].

Detailed condition assessment of stone objects has often been associated with labor-intensive analog or computer-aided design (CAD)-based mapping, which requires well-trained personnel [16]. Restorers often use mapping software, which still uses 2D maps or images as a reference and is therefore useful only for relatively planar historic surfaces, such as walls or façades. Commercial 3D mapping software does not always provide satisfactory results and is not user-friendly [17]. On the contrary, approaches centered on segmenting 3D models based on the surface [18] or reflectance [19] properties present greater accuracy and represent the real situation about deterioration more closely. Detailed 3D mapping can be achieved by classifying color and spectral information, by segmenting exported orthophoto-mosaics or UV maps and projecting the classification results back onto the 3D model of an object [20]. Specifically, the use of near-infrared (NIR) intensity textures can be of great value for decay mapping [21].

2 Overview and Methods

This short article discusses applying the techniques mentioned above for 3D digitization, visualization, and mapping of the state of preservation of stone heritage, through the case study of a bust of Franz Joseph I of Austria from the *Accademia Carrara di Bergamo* (Fig. 1). The authors aim to present the progress made in the experimentation with digitization and computational methods to evaluate workflows for accurate and less labor-intensive for conservation planning.

The object's geometric recording was performed with a structured-light system and with digital photogrammetric approaches to obtain diverse data types. SLS was performed with a handheld STONEX F6-SR structured-light scanner. Imagery for

SfM/DMVR approach-based reconstruction was robustly captured with a modified Canon Rebel SL1 camera, employing an 18.0 MP CMOS sensor. A UV-NIR-cut external filter was used for the color images, and a NIR-pass filter (700–1400 nm) was used to capture near-infrared reflectance images. The Mantis Vision Echo Software 1.2.0 was used for SLS, while Agisoft Metashape Professional 1.5.1 was utilized for the photogrammetric processing.

Post-processing of the scanned 3D point clouds, application of different visualization techniques, and segmentation of the 3D models based on RGB and near-infrared textures were performed in CloudCompare, as well as the metric validation of the photogrammetric results. The classification of images and models' textures was implemented in MATLAB through K-means clustering-based image segmentation, using k-means++ algorithm for cluster center initialization. The number of clusters was chosen by roughly identifying the number of present deterioration patterns, according to the 'Illustrated glossary on stone deterioration patterns' [22] and by considering that at least one cluster should correspond to the healthy materials' surface.

Fig. 1. A view of the bust of Franz Joseph I.

3 Application and Results

The scanning of the busts' complex geometry resulted in many partial 3D point clouds that had to be co-registered through an Iterative Closest Point (ICP) algorithm and merged into a single point cloud. The resulting point cloud was cleaned, denoised, and then meshed (Poisson Surface Reconstruction). Despite the incomplete digitization inside the Echo Software, the visualization of the NIR intensities recorder by the structured-light scanner could give a decent first idea of the weathering stages on the bust's surface (Fig. 2). In addition to that, the SLS-derived model contained less surface noise than the ones produced with photogrammetric procedures.

The 3D models generated with image-based approaches from RGB and NIR imagery were metrically validated by comparing them to the ground-truth model produced with SLS. In both cases, mean Hausdorff distances estimated with the appropriate measurement tool in CloudCompare ranged below 1 mm. Furthermore, the two models had between them remarkably similar density, surface characteristics, and the distances calculated between the two surfaces were, on average less than 0.5 mm.

Shading of meshes' surfaces was based on approximate normal rendering with the Eye-Dome Lighting (EDL) shader, approximate ambient occlusion rendering with the Screen space ambient occlusion (SSAO) [23] shader, and applying Sobel filtering [24] over anisotropic diffusion filtered images to obtain gradient maps of the surface. The results, shown in Figure 3, and particularly rendering according to SSAO and gradient vectors gave more interpretable visualizations of the surface's characteristics.

Fig. 2. Partial SLS-produced model textured with the F6 SR scanner intensities.

Fig. 3. Visualizations of digital model in CloudCompare with approximated normal rendering using SSAO shader (left) and Sobel filter-based solution (right).

Photogrammetrically-produced models are illustrated in Figure 4. After transferring the NIR intensities from the texture mosaic image-file to the model's surface triangles, a direct segmentation of the weathering stages was achieved by directly segmenting in 3D according to the grayscale values. This segmentation had good correspondence with the real-life situation about degradation, as seen in Figure 5. The segmented surfaces' area could be measured, which has significant value for the conservation interventions' efficient planning.

Fig. 4. Digital models produced with image-based techniques: untextured (left), textured (right), produced with RGB imagery (top), and with NIR imagery (bottom).

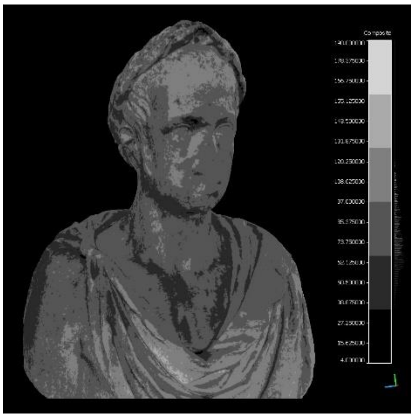

Fig. 5. Direct 3D segmentation of the model based on NIR texture to visualize stone weathering stages (darkest tone translates to a higher level of weathering).

The detailed classification of the deterioration patterns in 3D was implemented with two different techniques. The first included exporting RGB and NIR 2D ortho-mosaics of the bust's surface, blending them to create a multi-spectral pseudo-colored image, then classifying it with an unsupervised method, and finally back-projecting the 2D classification results onto the 3D object. The second technique was based on the NIR texture's direct unsupervised classification (Fig. 6). Results from the first implementation were more easily interpretable as specific segmented areas had an apparent correspondence to a particular type of deterioration. However, the projection of the classified ortho-mosaic onto the model created few gaps in the textured product due to the occlusions caused by complex geometry. Multiple partial classified ortho-mosaics on convenient planes would be needed to cover the full object and avoid the occlusions as much as possible. The second technique provided a classification covering the complete object without occlusion problems. However, in this case, results were not as easily interpretable because of errors created during the classification—due to areas that presented the same decay patterns but were unconnected on the texture image.

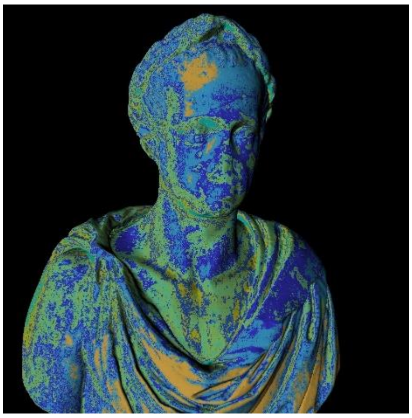

Fig. 6. 3D classification of deterioration using the near-infrared texture. Blue-colored areas correspond to healthier material, while green corresponds to biodeterioration and black crusts, and orange to stone patina.

4 Discussion and Conclusions

This paper presented digital approaches for visualizing the state of preservation for stone sculptures by combining contemporary image and SLS-based reconstruction approaches, rendering, and computational techniques. The different types of shaded visualization provided useful qualitative ways of interpreting the degradation of stone in 3D. However, the surface's segmentation based on thresholding of NIR intensities and 3D classification based on multi-spectral textures proved to have a significant advantage over the time-consuming analog mapping and 2D approaches which do not have metric qualities. Additionally, 3D classification approaches have the advantage that the identified deteriorated areas can be measured, providing important input for the decision-making on conservation interventions. The authors aim to explore further the methods described here by involving more intricate supervised classification techniques based on the conservators' input and machine learning algorithms. Additionally, the authors are interested in expanding the experimentation through interactive 3D visualization and by annotating information about the conservation state and historical information.

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