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Optical micro-profilometry for surface analysis and 3D printed replica of archeological artefacts

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***Abstract* – In this paper we present the potentialities of the conoscopic holography sensors for surface analysis of archeological artifacts with a micrometric resolution. The modularity and the portability of the developed setup allow to work in situ with a multi-scale and multi-material approach. Moreover, we developed our own tools for creating a mesh from the 2D-arrays of distances collected with the consequent possibility of printing a replica of the artwork using 3D printing technologies. We test the microprofilometer on two case studies: a fragment of an archeological amphora, presenting also the workflow to obtain the 3D printed object, and an Etruscan bronze mirror, analyzing the surface.**

I. INTRODUCTION

Non-contact optical systems are gaining more and more importance in many fields varying from quality control to robotics. Thanks to the ability to measure the surfaces in contact-less noninvasive way, these methods are ideal in the field of cultural heritage in which the surface of the object is the central and essential part of the artwork itself. In fact, the surface is often the most vulnerable part of the object because it is in direct contact with the environment and exposed to many external agents that can cause different degradation processes. For instance, porous materials can absorb water and the pollutants with the formation of salts. The crystallization process leads to efflorescence or subsurface mechanical stresses that can irreversibly modify the surface. Even surface cleaning or restoration processes eventually produce morphological and microstructural changes at smaller scales.

The surface of an artwork has an intrinsic multi-scale nature being a superimposition of a large number of spatial wavelengths. Moreover, cultural objects are unique entities made of different materials. The main challenges in artwork conservation and diagnostics are due to irregularity of the structure, polychromy and the need to obtain high-accuracy data in order to catch even the smallest details or defects. In this context, the digitalization of the surface is gaining importance not only for the documentation but also for providing useful information for monitoring its time and spatial variations or supporting restoration decisions. The basic and the first step is the artwork acquisition: accurate measurements are necessary for an accurate representation of the object [1].

In this paper we present the versatility of a prototype of optical scanning microprofilometry as a tailored technique to in-situ diagnostics of artworks. This system is based on the conoscopic holography principle and it is a possible technique to acquire 3D archeological surface with micro-metric resolution. Thanks to the adaptability of the conoscopic holography sensors, this system is able to operate with irregular shapes, composite materials and polychrome surfaces leading to a multi-scale and multi-material approach of surface analysis [2]. Finally, the acquired data can be used to create the mesh file in order to process the artwork using the 3D printing technologies and to obtain an accurate replica of the object. In fact, 3D printing technologies are gaining more and more attention in the field of cultural heritage and 3D printers are now easily accessible to museum and institutions. Thanks to the possibility to reproduce the artworks, 3D printed object can be used for restoration and conservation reasons, haptic fruition and many other purposes [3]. Moreover, 3D printing has gradually gained better levels of accuracy and, in some cases, the resolution achievable could be greater than the resolution of some acquisition systems.

II. CONOSCOPIC HOLOGRAPHY SENSORS

The conoscopic holography technique is based on the recording of the interference pattern formed between an object beam and a reference beam using a coherent light source (Figure 1). In details, a laser beam traverses an optically anisotropic crystal and is split into two beams. The two beams share the same geometric paths but have orthogonal polarization modes. The refractive index of the crystal varies depending on the angle of incidence of the beam and on its polarization state causing a difference in the optical path length. Therefore, after the two beams exit the crystal, an interference pattern is produced [4], [5]. The characteristics of the generated pattern depend on the distance of the sampled surface from the light source.

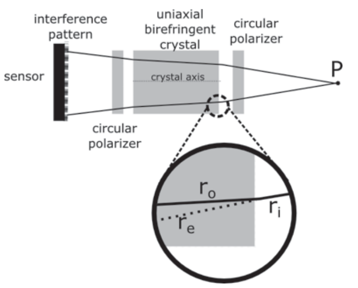

Figure 1: Schematic conoscopic holography principle representation.

The main advantages of conoscopic holography sensors are:

- Contact-less measurement;
- Sub-millimeter spatial resolution;
- Precision down to a few micrometers;
- Specular reflective and diffusive surfaces can be acquired;
- Single-point sensor and scanning techniques allow the creation of profiles and surface maps with custom "field of view";
- The collinearity of the set-up allows to measure the depth of holes and cracks without incurring in shadows effects.

The system is designed starting from conoscopic sensors distributed by Optimet [6]. The multi-probe module includes a sensor for diffusive materials (ConoPoint3), a sensor for reflective materials (ConoPoint3HD), and a sensor for specular or transparent surfaces (ConoPoint3R). Each probe can be then equipped choosing between several lenses to perform surface acquisition in different working range, i.e. maximum step-height. The different combination of sensors and lenses allows the analysis of reflective materials with a maximum accuracy of 1 μm and working range of 1 mm up to a working range of 9 mm with an accuracy of 4.5 μm. While for diffusive material it is possible to achieve an accuracy of 2 μm with a working range limited to 0.6 mm or extending the working range up to 180 mm maintaining a sub-millimeter accuracy of 100 μm.

The sensor measures a single point hence for reconstructing a surface the probe must be moved following a controlled path. The scanning setup that we assembled for performing the scanning is composed by a motion system with linear axis stages (by PI) orthogonally mounted to form the acquisition grid (X, Y axis). The axes have a maximum travel range of 300 mm and a step precision of 0.1 μm with an accuracy of 1 μm over the entire length. The horizontal axis (X) can travel up to 50 mm s^{-1}, the vertical axis (Y) up to 3 mm s^{-1}. The probe operates in pulse-mode, receiving pulses from an external trigger sent by the scanning system: for each pulse the probe acquires the distances from the lens to the sampled object. The software reconstructs a 2D array of distances from the data recorded knowing the number of measurements for each line and the direction of motion.

We designed two set-ups (Figure 2): in the first one the probe is in a still position while the micrometric stages move the sample; in the second set-up, which is useful for in-situ measurements when the object cannot be moved, the probe is mounted and moved by the two motorized linear stages.

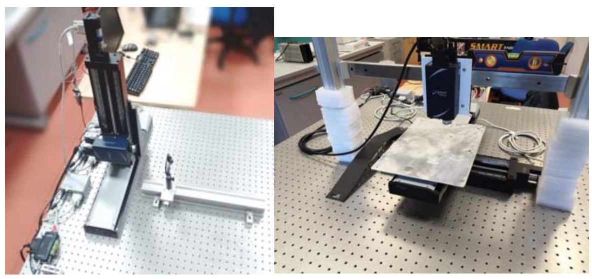

Figure 2: Left: setup with the object in still position on vertical plane. Right: setup with the probe in still position and object on horizontal plane.

III. EXPERIMENTAL APPLICATIONS AND DISCUSSION

A. Laboratory application: fragment of amphora

We test the micro-profilometer on a curvilinear porous surface: a portion of an archeologic amphora. The scanning setup is of the first type with the probe in still position and in details it is equipped with the ConoPoint-3 with a 75 mm lens. The working range is 18 mm with a stand-off distance of 70 mm and a laser spot size of 47 μm. We acquired a selected region of interest of 55.2 × 80.1 mm with a scanning step (X-Y sampling grid) of 100 μm and a scanning speed of 10 mm s^{-1}.

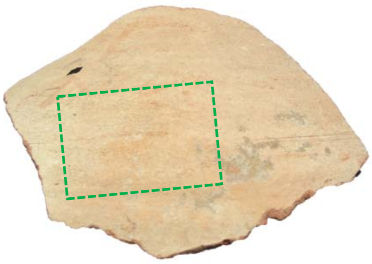

Figure 3: Part of archeologic amphora with the scanned ROI in green.

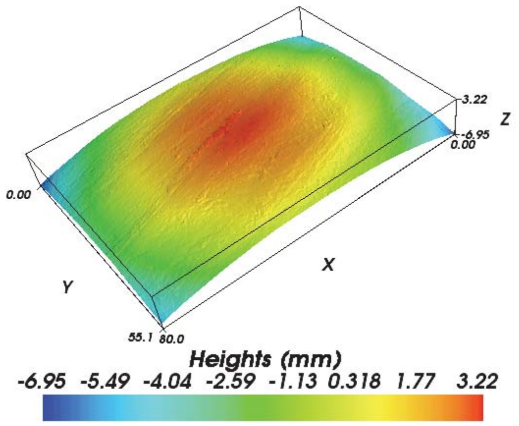

Figure 4: Surface map of the ROI of the amphora.

From this example we can notice that the signal of the surface of this object can be described as superimposition of different frequency components. In fact, the common approach in surface metrology is to separate the surface in three main components: the roughness, i.e. the irregularities at smaller scale that exhibit a random nature, more related to the behavior of the material; the waviness, i.e. the more widely spaced variation often associated with the traces left by the tool used for shaping the object; and the form, i.e. the 3D shape of the object. The image below shows the signal decomposition: a polynomial fitting enables to separate the shape from the texture, while the roughness is separated from the waviness using a Gaussian filter.

The importance of the surface signals separation lies not only in the possibility of having an insight on the production process of the object but also an insight in the conservation history of the object, assessing variations of roughness or surface features due to degradation processes or cleaning methods. It should must underlined, anyway, that in case of historical artefacts is not always possible to apply the rigid metrology classification from the engineering field.

Analyzing the pattern, we can see that the waviness contains some of the signs left by the potter at lower frequency that have an average spacing of 16.4 mm and an amplitude of 462 μm (maximum peak-to-valley distance). Besides this signal, a higher frequency signal is visible. This is probably due to a finishing with dried straw brushes. This signal has an average spacing of 1 mm and an average amplitude of 35 μm.

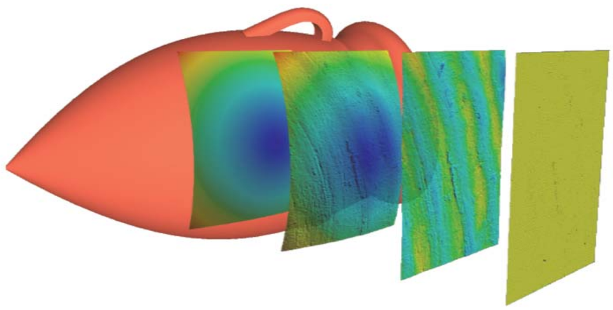

Figure 5: Schematic surface signal decomposition.

3D printing

From the analysis of the dimensional ranging of the feature encountered on the object that we want to reproduce, we can tailor the printing so that these meaningful details are not lost in the processing of the replica. Most of the profilometers do not store the data as a point clouds or mesh so that they cannot be printed directly. We developed our own tools for creating a mesh from the 2D-arrays of distances collected using the microprofilometer following this workflow:

1. From the scanning step we generate a grid of equally spaced point.
2. Once we have obtained the point cloud data with the triplet (X,Y,Z) representing the vertices of the mesh for creating a "watertight" solid, we generate the faces and hence a cuboid with the same dimension of the scan and we substitute the top face with the scan
3. Eventually, we can programmatically create and export the mesh to a STL file using Trimesh [7]. An STL describes the surface geometry of the 3D object and it is the typical file format used by 3D printing and computer aid manufacturing.

The figure below shows the 3D printed object, created using Stereolithography (SLA) technology with a print resolution of 0.05 mm.

Figure 6: 3D printed ROI of the amphora.

To optimize the use of the printing material we can decide to extrude the surface for only a small distance, avoiding printing the entire thickness of the object. For maintaining the strength of the surface, in case we can print a support grid.

In order to test the accuracy of the 3D printing process of the artwork we measured the printed object. As example, the following figure shows the comparison of the amplitude distribution function of the higher spatial frequencies, i.e. waviness+roughness, which are the components mostly affected by the printing process.

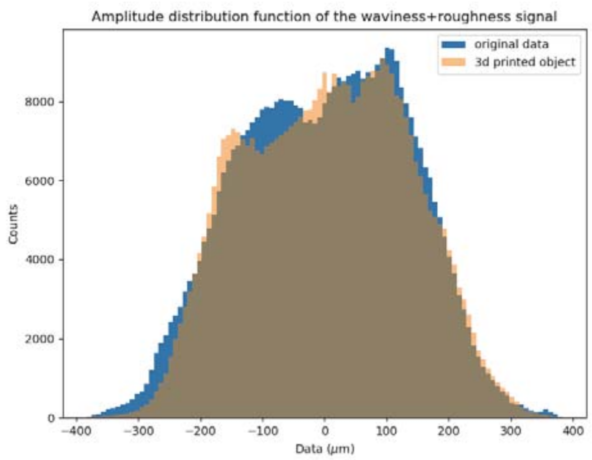

Figure 7: Comparison of original surface data and 3D printed replica.

B. Museum application: surface analysis of an Etruscan bronze mirror

The second application aims to show the potentiality of the micro-profilometer for in situ surface analysis in an out-of-lab environment. The interdisciplinary case study regards an Etruscan mirror that was investigated in collaboration with the Museum of Archeological Sciences and Art of the Department of Cultural Heritage of the University of Padua.

Historical description of the object

The object that has been investigated is a round bronze mirror, it has a diameter of around cm 14 and it is an Etruscan artifact, dated to the 4th century B.C. (Inv.nr.BT154

It belonged to the Neumann collection in Trieste until the whole collection passed to the University of Padua in 1925. In the following year the archeological part came to the University Museum of archeological Sciences and Art in which it is still today. As large part of that collection, the mirror's original place of finding is unknown.

The mirror was made by using a die casting and subsequently it was decorated with a carved decoration representing a mythological figure. Unfortunately, part of the mirror's plain surface and of the tang to connect it with the handle (not preserved) are missing. On the surface there are also several traces of corrosion and scratches.

With regard to the image, the lower part of a winged figure is preserved. It is a winged woman, dressed in classical clothes and wearing footwear. She is represented while walking to the left between two large flowers at her feet. The winged woman is perhaps a Lasa, a personage of the Etruscan pantheon who is represented on several Etruscan artifacts, especially on the mirrors. There are many interpretations of this mythological figure: she continues to raise questions and her role in the Etruscan religion remains disputable. Recent comparisons of the nameless figures of winged women to Lasa suggested that the name Lasa should not be applied to any winged female figure and it would be more suitable to use the term "Pseudo-Lasa". In addition, the meaning of this figure should probably be treated as connected with the world of women [8], [9].

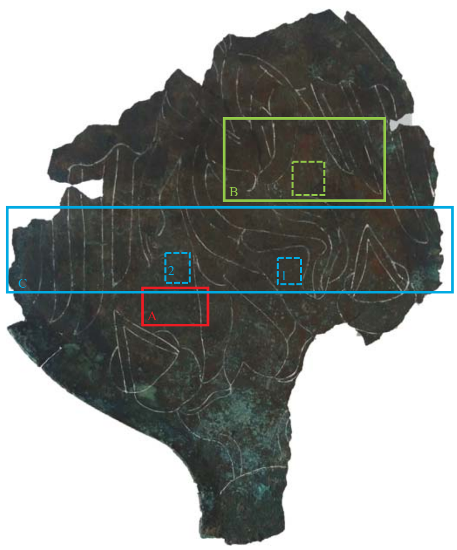

Figure 8: Etruscan mirror with the three investigated ROIs.

The following pictures show the surface intensity map of ROIs acquired by the micro-profilometer equipped with the ConoPoin3 and a 75 mm lens. The scanning step (X-Y sampling grid) was set at 50 µm and the scanning speed at 10 mm s^{-1}.

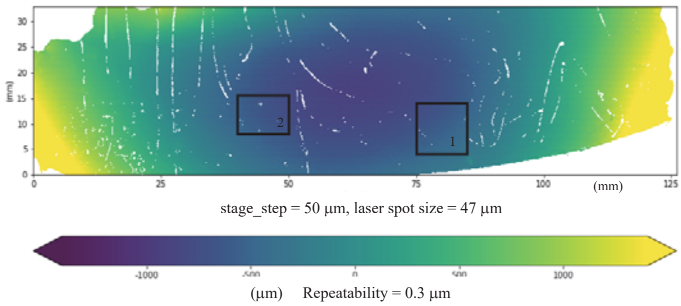

Figure 9: ROI C acquired by the microprofilometer with the two regions used for roughness analysis.

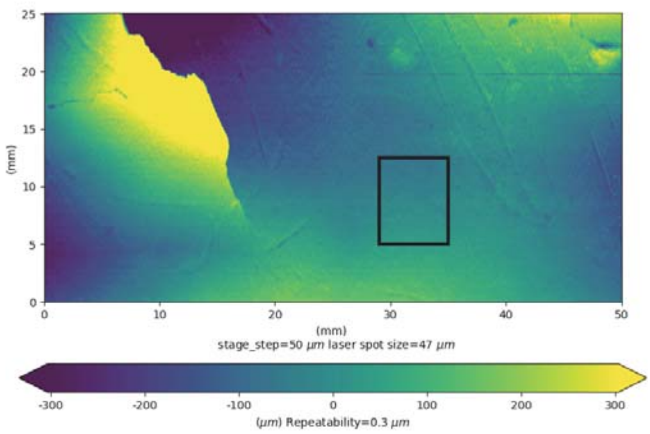

Figure 10: ROI B acquired by the microprofilometer with the region used for roughness analysis.

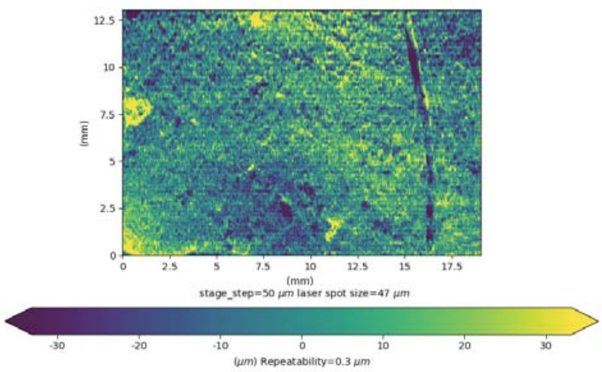

Figure 11: ROI A acquired by the microprofilometer.

We can compare the roughness computed as the standard deviation of the sections, after the removal of the form, in ROIs A, B, and C (Table 1). The ROIs exhibit a different texture probably due to different deterioration and cleaning processes.

Table 1: Measured surface parameters of the investigated ROIs.

	ROI A	ROI B (detail)	ROI C (detail 1)	ROI C (detail 2)
Roughness (µm)	16	34	24	30
Max peak-to-valley (µm)	212	177	208	225

From ROI A we can estimate the mean height of the corrosion spot around 71.5 µm.
The various ROIs highlight the incisions of the decoration with a measured width that varies from 50 to 650 µm and a measured depth that varies from 237 to 41 µm.
Moreover, ROI B presents a significant crack that causes a shift along the z axis. The maximum plane displacement measured in the investigated section is 0.93 mm.
From ROI C the average deformation is evaluated after the removal of the tilting plane. As can be seen in figure 12, the object shows a maximum displacement along the x axis is near 2 mm with the greater curvature in the middle.

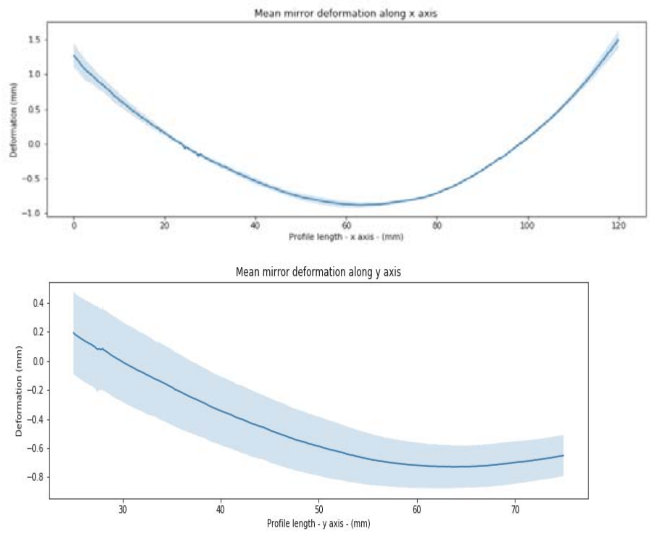

Figure 12: Mean curvature of the mirror measured along the x axis (top) and the y axis (bottom) of the central part of ROI C, using respectively 200 rows and 1000 columns.

III. CONCLUSION

In this work we presented the potential applications of the scanning conoscopic holography on archeological objects.

The following characteristics make the developed micro-profilometer prototype an optimal tool for artworks acquisition and surface analysis:

- the accurate data acquisition process, at micro-scale, without the need of contact with the sample;
- the versatility of the configuration setup, which allows both laboratory acquisition of sample than measuring in situ artworks of large dimensions or too frail to be moved;
- the system modularity, with the possibility of setting different spatial samplings for different needs by coupling different lenses and laser probes.

The micro-metric resolution is of fundamental importance for the acquisition of the material surface texture in artworks, allowing the analysis of the roughness and waviness components with different aims, from the study of the historical features to the monitoring of the conservation status. The 2D array can be elaborated to obtain the file format suitable for 3D printing technology with the possibility to create a high-fidelity and high-resolution replica of the artwork.

Here, the optical micro-profilometry for surface analysis and 3d printing was demonstrated in two exemplar case studies: an archeological amphora and an Etruscan bronze mirror, investigated in collaboration with the Museum of Archeological Sciences and Art of the University of Padua (Department of Cultural Heritage).

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