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OPTICAL MICROPROFILOMETRY OPTIMIZED FOR SURFACE ANALYSIS AND 3D PRINTING OF ARCHAEOLOGICAL OBJECTS

1. Introduction

Non-contact 3D optical systems are gaining more and more importance in many fields varying from quality control to robotics (Sansoni *et al.* 2009). Thanks to their ability to measure the surfaces in contact-less non-invasive way, these methods are ideal in the field of cultural heritage when the surface of the object is the central and essential part of the artwork itself. The primary aspect concerns clearly the aesthetic appearance of the object that is the crucial part for professionnals and non professionnals in the field of cultural heritage. However, the cultural assets, and in particular the archaeological objects sustain and reveal the passage of time: if on one side the signs confer to the object the charm of history, on the other side they can reveal deterioration processes. 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 (Striova *et al.* 2016; Daffara *et al.* 2017).

The surface of an artwork has an intrinsic multi-scale nature being a superimposition of a large number of spatial wavelengths. Beside the surface texture, also the surface deformation, namely the small deviations from the main shape of the object, may provide to archaeologist important insights on an archaeological artifact. Moreover, cultural objects in general 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 is gaining importance not only for the documentation but also for providing useful information for monitoring time and spatial variations or supporting restoration decisions. The basic and the first step is the artwork's data acquisition: accurate measurements are necessary for an accurate representation of the object (Gaburro *et al.* 2017b).

In this paper we present the versatility of optical scanning micro-profilometry as a tailored technique to *in situ* diagnostics and documentation of archaeological objects. The method is based on laser interferometry, specifically, on the conoscopic holography principle, and thus it is a possible technique to acquire the 3D archaeological surface with micrometric resolution. Thanks to the adaptability of the conoscopic holography sensors and the scanning system, this technology is able to operate with irregular shapes, composite materials, and polychrome surfaces, thus leading to a multi-scale and multi-material approach in surface analysis (Gaburro *et al.* 2017a).

A further advantage of scanning profilometry, as argued in this paper, is that the acquired data can be used to create the mesh file in order to produce an accurate replica of the artwork using 3D printing technologies. 3D printing process could be a considerable support in the field of archaeology where the replication of objects could play a key role in a number of core activities (Balletti *et al.* 2019). In addition, these technologies are gaining attention in the entire field of cultural heritage and 3D printers are now easily accessible to museums and institutions. Thanks to the possibility to reproduce the artworks, 3D printed object can be used for restoration and conservation, haptic fruition and many other purposes (Balletti *et al.* 2017). Moreover, as described in literature (Wilson *et al.* 2018, 2020) museums have progressively focused their attention to a more user-centered fruition in which the visitors make use of a range of senses beyond sight. In this contest, it is pointed out that the most valued aspect for the printed replica is to be realistic and to represent the original object at the best. 3D printing has gradually gained better levels of accuracy and the resolution achieved is now compatible with the resolution of optical acquisition systems, in particular the scanning profilometer based on conoscopic holography, the use of which for 3D archaeological replicas is an innovative application.

2. Optical scanning profilometry based on conoscopic holography sensors

The conoscopic holography technique is based on the recording of the interference pattern formed from an object beam and a reference beam using a coherent light source. The backscattered laser beam is split into two by an optically anisotropic crystal, which has a refractive index that depends on the incidence angle and the polarization state of the ray. This property allows the two rays to share the same geometric path but to have a different optical path length. Therefore, after the two beams exit the crystal, they can interfere to each other and the characteristics of the generated pattern depend on the distance of the sampled surface from the light source (Sirat 1992; Álvarez *et al.* 2009).

Each probe can be then equipped choosing between several lenses to perform surface acquisition in different working range that is the maximum z-displacement that can be acquired. The different combination of sensors and lenses allows the analysis of reflective materials with micrometric accuracy in millimetric scales, namely with a working range of 1 mm up to a working range of 9 mm. While for diffusive material it is possible to obtain a working range that varies from 0.6 mm up to 180 mm maintaining a sub-millimetric accuracy. 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 orthogonally mounted to form the acquisition grid (X, Y axis). The axes have a maximum travel range of 300 mm that allows acquiring significative regions, i.e. small archaeological objects, or selected parts with well defined macroscopic features (e.g. incisions, reliefs, scratches, etc.). 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 different set-ups suitable for different applications. In the first one the probe is in a still position while the micrometric stages are fixed on an optical table and move the sample. This configuration is particularly useful when there are small archaeological samples that can be analysed in the laboratory like ancient coins, earthenware, shards, bone fragments, etc. Instead, the second set-up is suitable for *in situ* measurements, i.e. when the object cannot be moved, as for example in the case of mural painting, fixed relief or large tridimensional objects that is advisable to not move outside the museum. In this case the probe is mounted and moved by the two motorized linear stages while the object remains stationary.

3. Experimental applications and discussions

3.1 *Laboratory application: fragment of amphora*

We present a first application of the technique in a laboratory environment on a curvilinear surface: a portion of an archaeologic amphora (Fig. 1, left). The scanning setup is conveniently of the first type with the probe in still position 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}.

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;

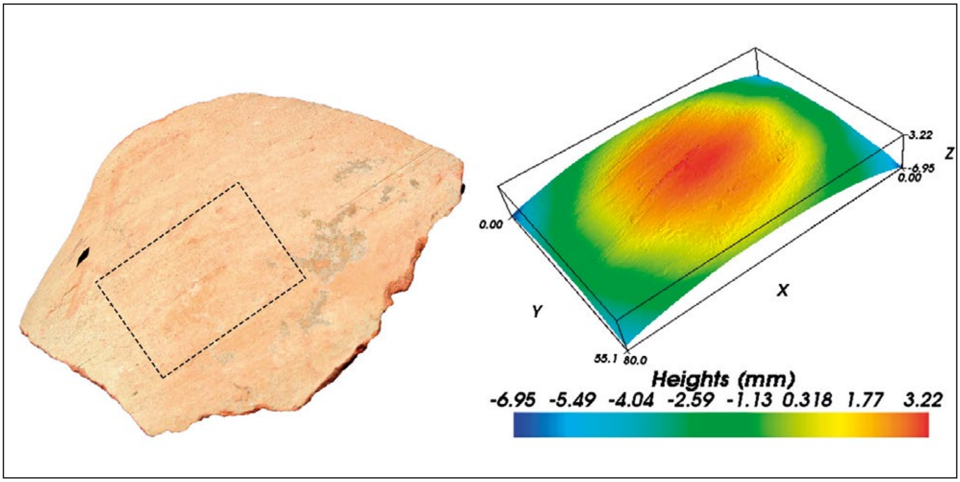

Fig. 1 – Left: part of the amphora with the scanned ROI of 55.2×80.1 mm^2 (black dashed line); right: surface map of the ROI.

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. In the case of the region of interest (ROI) of the amphora we decompose the signal using a polynomial fitting 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 changes due to degradation processes or cleaning methods. It should underline, anyway, that in case of historical artefacts is not always possible to apply the rigid metrology classification. Analysing 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.

3.2 3*D printing*

From the analysis of the dimensional ranging of the features encountered on the object that we want to reproduce, we can tailor the printing so that these meaningful details are not lost in the process. 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:

– from the scanning step we generate a grid of equally spaced point;
– 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;
– eventually, we can programmatically create and export the mesh to a STL file using Trimesh (Trimesh). 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 (Fig. 2, left) shows the 3D printed object that we tested and printed using the best possible resolution (0.05 mm) of a commercial printer that employs the stereolithography (SLA) technology. 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 (Fig. 2, right) 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.

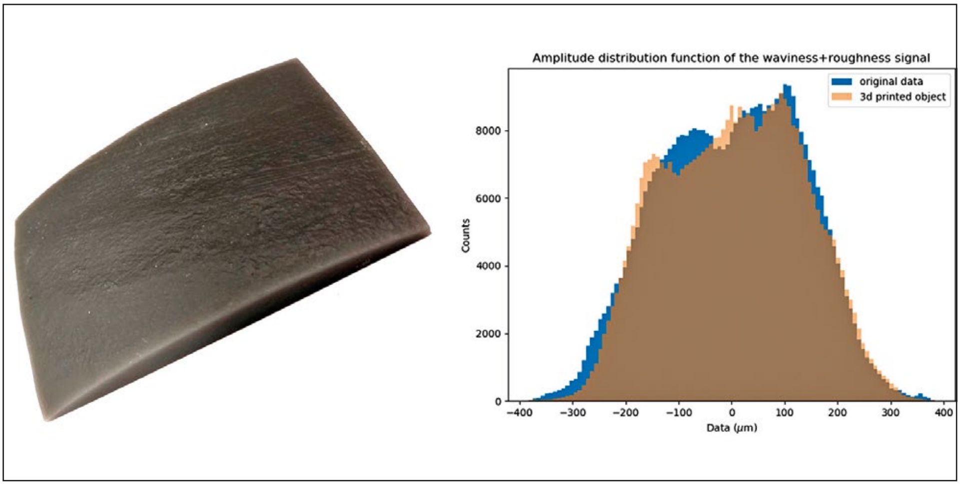

Fig. 2 – Left: 3D printed ROI of the amphora. Right: comparison of original surface data and 3D printed replica.

3.3 *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 Archaeological Sciences and Art of the Department of Cultural Heritage of the University of Padua.

3.3.1 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 artefact, dated to the mid/second half of the 4th century BC (Inv. 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 archaeological section came to the University Museum of Archaeological Sciences and Art in which it is still today. As the 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 decoration (Fig. 3), 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 figure of the

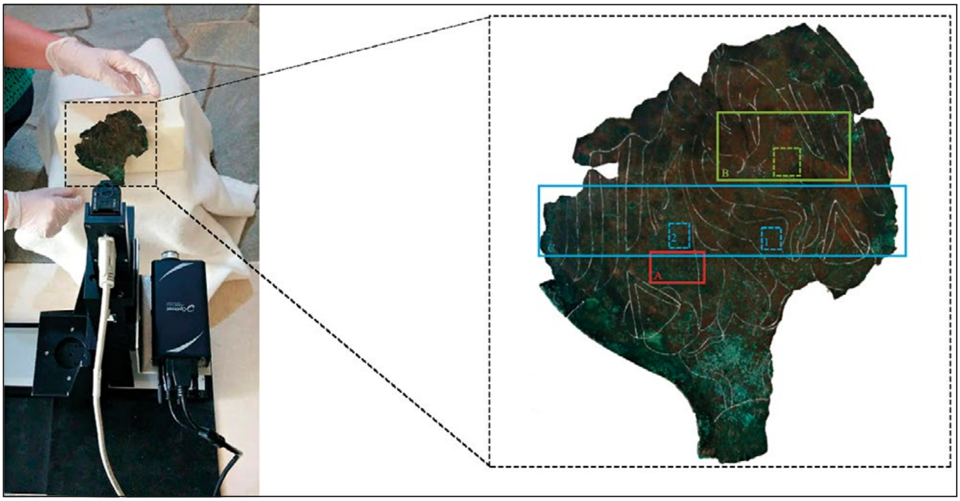

Fig. 3 – Left: *in situ* measurements of the mirror; right: the considered object with the investigated ROIs.

Etruscan pantheon who is represented on several Etruscan artefacts, 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 female world (Spiller 1970; Korczyńska-Zdąbłarz 2011).

3.3.2 Data acquisition and analysis

Fig. 4 shows the surface intensity map of the 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}. 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 (Tab. 1). The ROIs exhibit different textures probably due to different deterioration and cleaning processes.

	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

Tab. 1 – Measured surface parameters of the investigated ROIs.

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 following plots (Fig. 5), the object shows a maximum displacement along the x axis near 2 mm, with the greater curvature in the middle.

4. Conclusions

In this work we presented the potential of scanning conoscopic holography applications on archaeological objects. Among the main potentialities of the technique there is the possibility to perform contact-less and full-field measurements with a micrometric precision, taking advantages of a versatile configuration setup that allows both laboratory acquisition of samples than measuring *in situ* artworks of large dimensions or too frail to be moved. Specifically, the system modularity allows the possibility of setting different spatial samplings

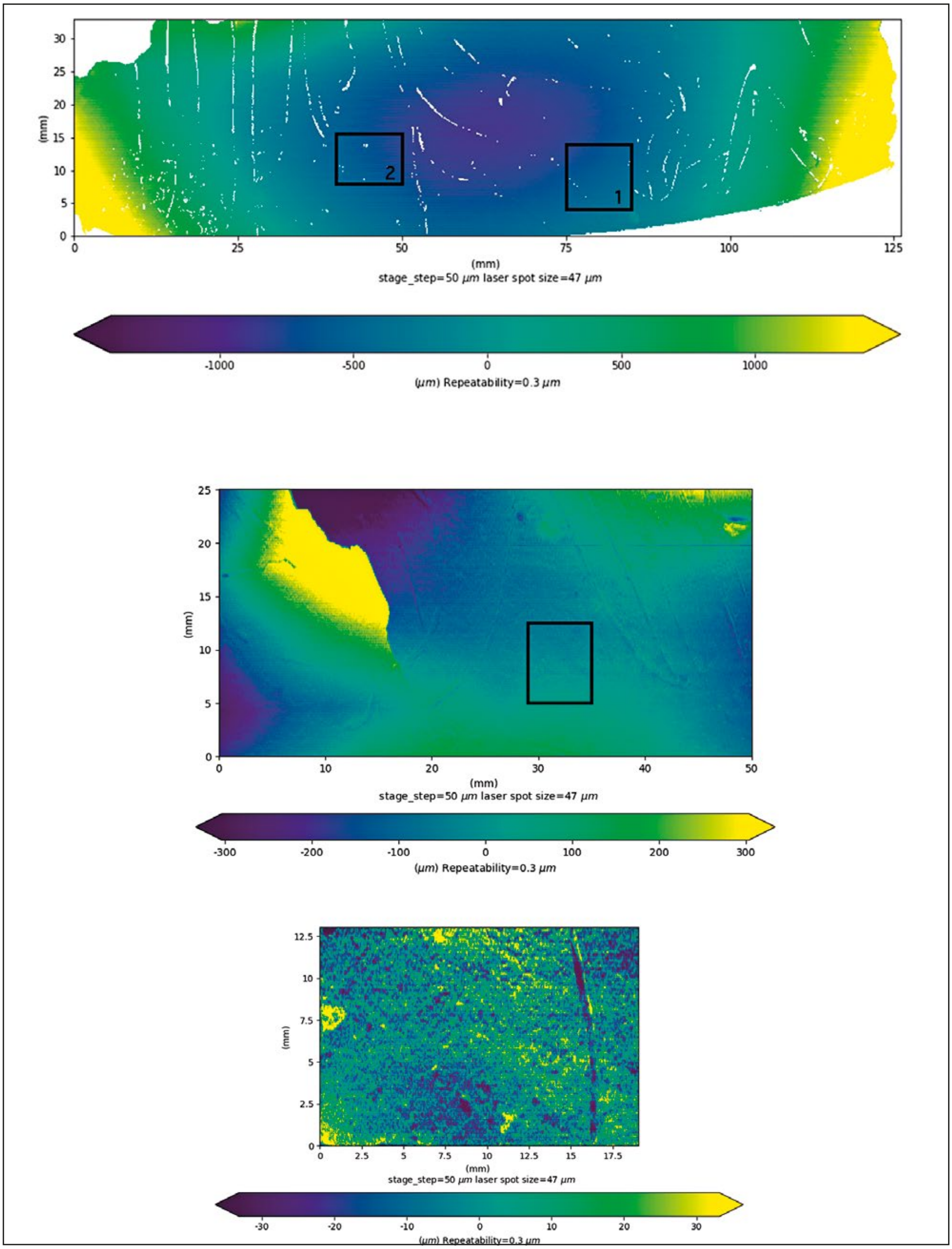

Fig. 4 – Top: ROI C acquired by the microprofilometer with the two regions used for roughness analysis (1:10×10 mm², 2: 10×7.5 mm²). Middle: ROI B acquired by the microprofilometer with the region (6×7.5 mm²) used for roughness analysis. Bottom: ROI A acquired by the microprofilometer.

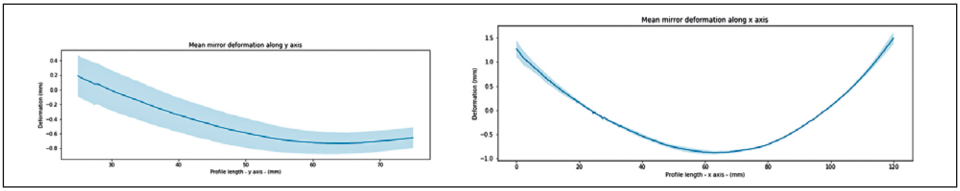

Fig. 5 – Mean curvature of the mirror measured along the x axis (left) and the y axis (right) of the central part of ROI C, using respectively 200 rows and 1000 columns.

for different needs by coupling different lenses and laser probes. Then, there is the advantage of using a single-point sensor and scanning techniques that enable the creation of profiles and surface maps with custom 'field of view'.

The micro-metric resolution is of fundamental importance for the acquisition of the material surface texture in an archaeological object, allowing the analysis of the roughness and waviness components for different aims, from the study of the historical features to the monitoring of the conservation status. Furthermore, the 2D array can be elaborated to obtain the file format suitable for 3D printing technology with the possibility to create an accurate and high-resolution replica of the artwork. The 3D printed replica of objects offers new possibilities for the museums or in the field of experimental archaeology, especially if it starts from accurate and precise acquisitions. Obviously, this adds new levels of challenges, but at the same time, it can lead to the opportunity to develop a multidisciplinary research. Here, the optical micro-profilometry for 3D printing and surface analysis was demonstrated in two case studies: a laboratory application on a fragment of an amphora, and an Etruscan bronze mirror investigated *in situ*, in collaboration with the Museum of Archaeological Sciences and Art of the University of Padua.

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Sara Mazzocato, Claudia Daffara
Department of Computer Science, University of Verona
sara.mazzocato@univr.it, claudia.daffara@univr.it

Giacomo Marchioro
Department of Cultures and Civilisations, University of Verona
giacomo.marchioro@univr.it

Alessandra Menegazzi
University Museums Centre (CAM), Padova
alessandra.menegazzi@unipd.it

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ABSTRACT

In this paper we investigated the application of the optical scanning micro-profilometry based on conoscopic holography sensors for the acquisition and the surface analysis of archaeological objects with a micrometric resolution. The portability of the setup developed and its modularity allow to work *in situ* with a multi-scale and multi-material approach. In addition, we have developed our own tools to create a mesh from the 2D-arrays of distances collected with the resulting possibility to obtain a replica of the artwork using 3D printing technologies. We test the micro-profilometer on two case studies: a fragment of an archaeological amphora, also presenting the workflow to obtain the 3D printed object, and an Etruscan bronze mirror, analyzing its surface.