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3D digital microscopy for characterising punchworks on medieval panel paintings

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This paper is devoted to novel technical features and applications of micro-3D modeling. A 3D portable digital microscope prototype, developed for this purpose, has been used for the first time in order to analyze gold punchwork on medieval panel paintings. In general, the 3D domain provides a more flexible and complete characterization of these decorative elements than traditional photographic documentation. Low magnification 3D digital microscopy is well suited for analyzing morphologies, depths and profiles of different punch marks. Here, we used these parameters for interpreting the punching process and recognize sliding and bouncing effects. The 3D reconstruction of the surface engraved also allowed identifying types of anomalies that could be useful as possible authentication markers. The advantages of the present approach with respect to the photographic documentation are of general valence and can be exploited in order to document, parameterize, and interpret a variety of engraving works on panel paintings and metal artifacts.

Additional Key Words: Contour : 3D reconstruction

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1. INTRODUCTION

Most of the late medieval panel paintings include elaborated decorative punching of their gilded areas. Pattern-ended punches leaving particular marks (circles, rosettes, segmental arches, etc.) stroke with a single soft hammer blow were very frequent. Thus in particular, such a decorative finishing work was often carried out in order to enrich the aureoles of holy figures with complex patterns. Since each artist usually built his own

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punches, the micromorphological characterization of the latter could provide meaningful data, which could be exploited in attribution and authentication studies.

Artists of the 14th century generally had a widespread repertory of punches, which were often fabricated with similar sizes and motifs. The problem of distinguishing between analogous punches marks reduces its difficulty as the complexity grows. In fact, a composite motif was commonly crafted by assembling several basic pieces, and its artistic attribution could be accomplished by isolating and/or by identifying each single element constituting the complex motif.

Several works have been reported on these topics [Sperber et al. 2011; Castelnuovo-Tedesco et al. 2010; Skaug 2008; Ward 2008; Strehlke et al. 2006; Monaco et al. 2006; Flintenborg 2005; Frinta 1998; Romano 1995; Skaug 1994; Steinhoff-Morrison et al. 1990; Beatson et al. 1986; D. Gordon et al. 1985; Skaug 1971; Frinta 1965]. The common approach is based on stylistic appraisal, correlation in decorative pattern and in single punch marks, and associations among Late Middle Ages artists [Frinta 1965, Skaug 1971]. However, with few exceptions, these researches have not gone beyond general observations. This investigation procedure has been further complicated by the enormous number of paintings and their disseminated locations all over Europe, which are not easily accessible to the scholars, as well as by the general preservation conditions of the paintings, which could make the morphological inspection very difficult.

In the literature there are only two notable examples of catalogues listing punch marks, and these are considered by the authors themselves to contain insufficient information in order to draw exhaustive conclusions [Skaug 1994; Frinta 1998]. This issue represents a stimulus for further insights.

Previous studies were essentially based on stereomicroscope examinations and for a long time images were recorded using photography. These 2D approaches could be considered out of date as many 3D imaging techniques are now considered established in the field of Cultural heritage and conservation [Sansoni et al. 2009; Poggi et al. 2005, Dellepiane et al. 2011; Zhang et al. 2012, Arbace et al. 2013; Patay-Horváth 2013].

Recently, 3D optical coherence tomography has been employed in the present framework [Adler et al. 2007]. However, the complex instrumental setup and data elaboration significantly limit the versatility and applicability of this technique, especially in view of a general cataloguing work. This drawback could be overcome with a more flexible technique such as 3D digital microscopy. We have developed a novel 3D digital microscope devoted to morphological and textural analyses [Cacciari et al. 2012a]. It has been successfully employed for different purposes, such as laser-treatment inspection of bronze archaeological artifacts and of sculptural stone elements [Cacciari et al. 2012b], or gold Etruscan jewels [Cacciari et al. 2013] or depth profiling for LIPS analysis [Siano et al. 2011], or combined with other techniques for analysis of genuine and fake copper-alloy coins [Bartoli et al. 2011].

In this framework, the 3D imaging content in terms of morphological information is definitely much richer than common 2D imaging. Thus for example, the possibility of misidentifying punch marks made with the same tool or vice versa could be eliminated, since each microscopic imperfection in the marks could provide the fingerprint of a particular punch tool. Here, we report the development of a novel portable 3D digital microscope based on the “shape from focusing” technique [Nayar 1994] with a compact setup and improved versatility and analytical performances with respect to other devices available on the market. The novel instrument was used in order to explore for the first time the potential of 3D microscopy modeling for investigating punchworks on panel paintings. We tested the novel approach on three of the most used punch patterns categories: circle, hexa and penta rosette, where the former included concave and convex tips. In particular, we investigated those used for decorating Simone Martini's Polittico di Santa Caterina d'Alessandria (dated 1320) from the Museo Nazionale di San Matteo, Pisa. All the mentioned punch marks were characterized in terms of lateral sizes, shapes and depths. At the same time, the technique was also used in order to highlight several aspects concerning the striking process. The present quick, reliable, and low-cost analytical approach and the data reported can represent the first step towards a recompilation of punch tool catalogues in the 3D domain.

2. MATERIALS AND METHODS

3D imaging of the punch mark was achieved using the "shape from focus" (SFF) technique. Its setup basically includes an optoelectronic imaging group (CCD digital camera and a fixed-focus objective) and a calibrated stage for translating this group along the optical axis. In this way, the camera can record a stack of images at different (and known) heights. As each image has different parts that are out of focus, a software has purposely been developed to exclude these regions from each image and to combine all the remaining data into a deep focus image (texture) and associated 3D model by combining the latter with height map. It is worth noting that in this way the 3D model preserves the original color information.

The software developed allows performing several analytical calculations such as image filtering, selection of a region of interest and then extract profiles along every direction, mono- and bi-dimensional roughness coefficients, eccentricity estimation of round shapes, and others. In the following, each 3D reconstruction is shown both with its original texture and using false colors with the corresponding height scales. The former have been used to present the first realistic 3D models of punch tips.

For the present study, the following 3D digital microscope setup was assembled. A x5 plan apochromatic objective (Mitutoyo) with 1.4 μm depth of focus was connected to a x12 optical zoom (Navitar mod. 50503) terminated with a focusing optics, which imaged the zone under examination onto a 1.3 MPx CCD camera. This provided a square field of view whose side varied between 2.55-0.95 mm, depending on the zoom magnification selected. Wider fields of view (up to 6 mm) were obtained by replacing the objective with a x1 lens. The whole assembly was mounted on a special mechanical support in order to cover the sizes of the panel painting under investigation (150 x 50 cm). This allowed the translation of the optical head (optical system and CCD camera) upon the painting without any contact with the artwork, as shown in Figure 1.

Fig. 1. 3D microscopy inspection of a panel painting by Simone Martini: experimental setup.

We investigated the punchwork decorations of Simone Martini's Polittico di Santa Caterina d'Alessandria (dated around 1320) and preserved in the Museo Nazionale di San Matteo, Pisa. It includes numerous sub-panels: in the central panel the Madonna with oly Child are depicted, and in the six nearby panels other Saints are represented. The painting is made of tempera and gold leaf on wooden panels. Settled on the surface and clumped in the interstices of the punch marks there was a layer of water-soluble matter, which has been preliminarily removed using a fat neutral emulsion of non ionic surfactants and white spirit in water. We have analyzed circles, penta and hexa rosettes [Frinta 1998a] located in the halo of the Holy Child in the central panel.

3. RESULTS

3.1 Software development

In cultural heritage domain the broad variety of materials, micromorphologies, size ranges, and characterization problems, requires the possibility to collect simultaneously micro-3D and chromatic information. Both these features often makes the 3D reconstruction using standard techniques challenging. The "Shape from Focusing" (SFF) offers a robust and accurate method for shapes and textures reconstructions from every kind of surfaces. The SFF technique elaborates a set of different images of the same scene, collected at different focal planes and affected by blurring (i.e. different sharpness). A mathematical operator is required to elaborate these images for extracting the areas focused along with a mathematical model, which is able to calculate the focus variation introduced by the image blurring.

In the literature, several approaches have been introduced, most of them are based on kernel convolution [Pertuz et al. 2013; Zhao et al. 2013; Muhammad et al. 2012; Pertuz et al. 2010; Mahmood 2010; Wu et al. 2009; An et al. 2008; Riaz et al. 2008; Malik at al. 2008; Sun at al. 2004; Subbarao et al. 1998; Nayar 1994; Subbarao et al. 1994]. This mathematical tool can be conveniently used to translate in their finite (discrete) form many multidimensional mathematical operators, including differential operators; it is then suitable in order to process sets of 2D images. We have tested several commonly used kernel operators, based on grey level, gradients, sum of modified Laplacian etc.. Their performances have been discussed both using gold standard shapes and artifacts of cultural interest. The unsatisfactory reconstruction quality achieved, has stimulated us to improve existing kernels and to develop a novel operator.

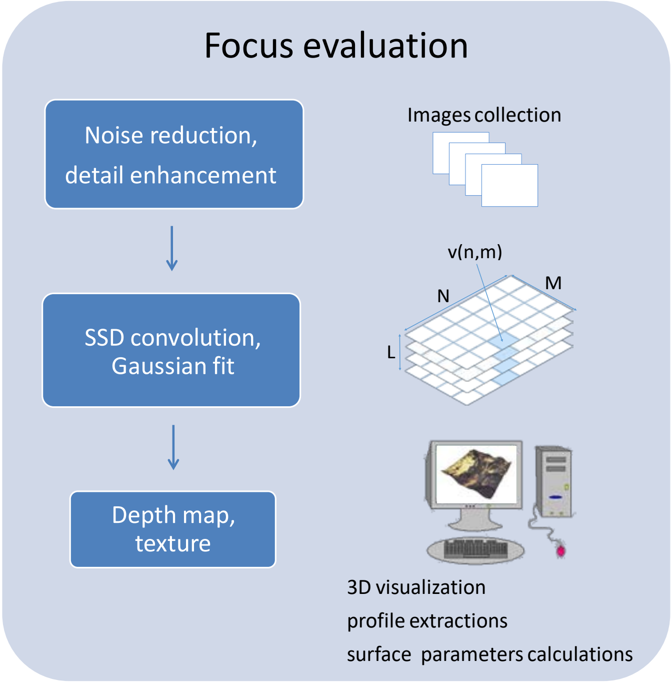

Fig. 2. Main stages of the 3D reconstruction algorithm

Our algorithm is based on three stages (Figure 2): 1) Noise reduction and details enhancement, 2) focus evaluation by kernel convolution, 3) 3D surface visualization and parameter extraction.

The first stage concerns some operations of noise reduction and details enhancement. The digital CCD camera captures images in RGB format at different and known heights, and a median filter is then applied. It removes both bright and dark isolated pixels and does not blur the contours. This operation helps to "clean" the images, especially when they are taken in low lighting conditions with high gain/long exposure camera setting, which often can give rise to spike-like noise. Every image is then converted in HSL (Hue, Saturation, Luma) format and considered the Luma plane. A logarithmic lookup table (LUT) transformation is applied to the Luma plane to enhance the sharpness for low intensities pixel.

In the second stage, the resulting image matrix (I) is ready to be evaluated in terms of local sharpness using kernel convolution $K \otimes I$, where K is an odd-dimensional matrix whose size defines the gauge area of the filter. The maximal spatial accuracy, which is required whenever modeling microscopic morphological details of archaeometric interest, is accomplished by a 3×3 matrix. We have defined a novel kernel operator, named Sum of Square Differences. It is the sum of the squares of differences between any couple of adjacent pixels closer to the one considered *(x,y)*.The resulting operator is made by three terms:

$$SSD = \frac{\sum_{i,j=\pm 1} \left(\begin{array}{c} \frac{1}{2}\left[\left(I_{x,y} - I_{x,y+j}\right)^2 + \left(I_{x,y} - I_{x+i,y}\right)^2 \right] \\ + \left(I_{x,y} - I_{x+i,y+j}\right)^2 \\ k\left[\left(I_{x+i,y+j} - I_{x+i,y}\right)^2 + \left(I_{x+i,y+j} - I_{x,y+j}\right)^2 \right] \end{array} \right)}{\left(\sum_{i=-1}^{+1} \sum_{j=-1}^{+1} I_{x+i,y+j} \right)} \qquad (1)$$

where the factor k is a weight assigned to closest pixels (distance=1), while for farther pixels (distance=$\sqrt{2}$) it has been set equal to 1. The quantity is normalized, in order to enhance the contribution due to the low-intensity pixels.

The kernel convolution is applied to every image, and the result is a 3D matrix ($NxMxL$), where NxM is the image size in pixel, L the number of images acquired by the digital 3D microscope at different focal planes. For each pixel (n,m) the local sharpness along the z-axis is represented by a L-elements vector (v) which is assumed to have a peak within the z-range explored. We have considered as mathematical model to calculate the focus variation introduced by the image blurring, a Gaussian function. For each vector $v(n,m)$ a Gaussian fit is then applied. The Gaussian center is the sharpest position for the pixel, $z_{max}(n,m)$, and the corresponding Standard Deviation SD(n,m) is related to the depth of focus. The matrix $z_{max}(n,m)$ is commonly defined as depth map, and contains the heights at which each pixel is considered in focus.

Finally, in the third stage, a low-pass filter is applied to $z_{max}(n,m)$ in order to properly smooth (de-noise) the 3D reconstruction. It is sometimes necessary to crop the map in order to cut out the original borders, which could be error affected by aberrations due to the optical system, especially when the input objective has large numerical aperture.

The corresponding RGB value of each pixel at focus position is extracted from the images collection to form one image, which is totally in focus. This image, is used as texture for color rendering of the 3D surface. At this stage several analytical calculations can be performed (selection of a region of interest and then extraction of profiles along every direction, calculation of mono- and bi-dimensional roughness coefficients, estimation of eccentricity of round shapes etc.)

The time needed for the whole processing based on the proposed SSD is similar to other kernel operator (such as Energy of Laplacian, Sum of Modified Laplacian, Variance Focus etc..). Actually, the Gaussian fit computation time (approximately two minutes for 100 images stack, 640x480 pixels) is much greater than that needed for any kernel convolution considered in preliminary works (a few seconds).

3.2 Application results

The surface of the punch marks have been reconstructed with their original texture and with one color-scale, and the shading of this color changes, depending on the resulting depth. As stated above, the developed software allows for the extraction of profiles from 3D surface reconstructions. In the paper, several profiles have been examined in order to measure several morphological features: in each image, an inset representing the textured image with the direction chosen has been included.

We have firstly considered simple circles. In Figure 3 the textured and the one color-scale reconstructions are presented. The area reconstructed is particularly interesting as it contains both convex and concave circular punch marks: it consists of a central large concave mark surrounded by densely repeated convex and smaller marks.

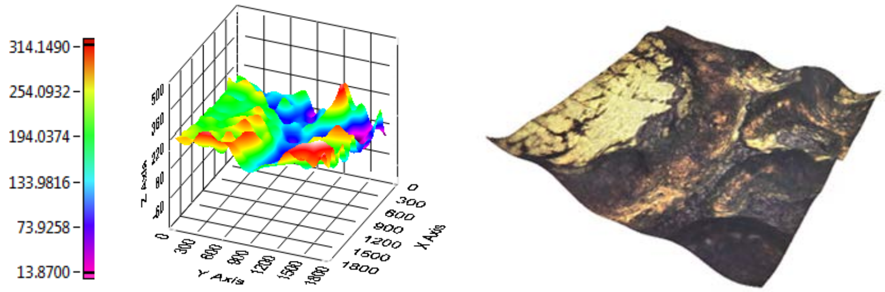

Fig. 3. 3D reconstruction of a concave punch mark surrounded by smaller convex marks.

From the reconstructions of Figure 3, several profiles have been extracted along the directions of interest (Figure 4). In this case, the main concern is the punch depth measurements: the central mark radius is 1 mm and 100 μm depth, the densely repeated concave marks have average radius and depth of 0.5 mm and 100 μm, respectively. This depth is found to be weaker (few tens of microns) in case of overlapped marks.

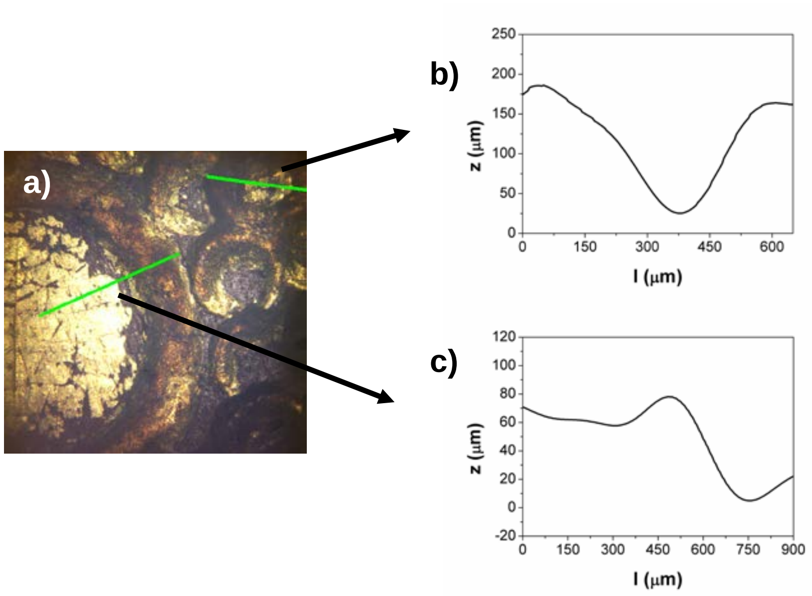

Fig. 4a. The morphology characterization is done by extracting two profiles along the lines from the 3D surface reconstruction. Fig. 4b Concave mark. Fig. 4c. Convex marks.

The second punch mark type considered, is represented by the hexa rosette [Frinta 1998a], whose 3D surface model is shown in Figure 5a. It consists of six petals around a central hole with a diameter of 0.5-0.6 mm. The resulting form is a flower with a 2 mm diameter, these data have been extracted from profiles such as the one shown in Figure 5b.

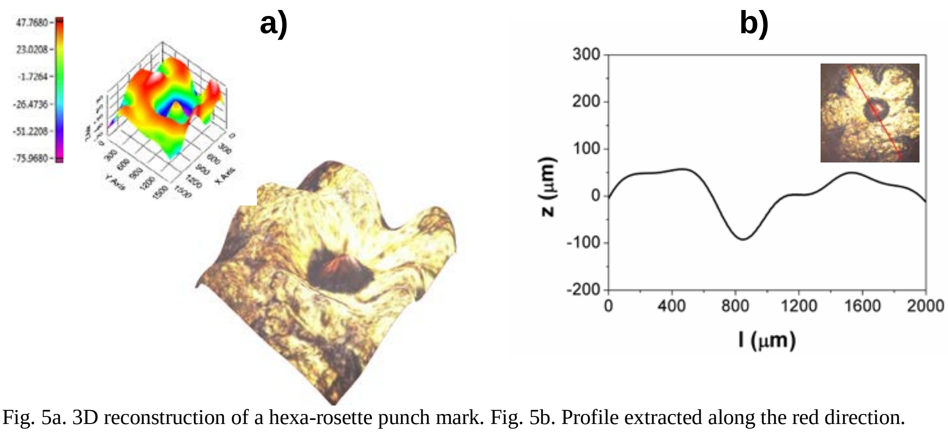

Fig. 5a. 3D reconstruction of a hexa-rosette punch mark. Fig. 5b. Profile extracted along the red direction.

Moreover, in the large amount of marks in a painting, it is likely to detect marks left by the same punch tool but characterized by some irregularities, f.i. an apparent multiple strike in the central hole observed in several hexa rosette marks. In Figure 6a an example of this kind of defect is presented. In Figure 6b and 6c two different views of the same mark reconstruction are displayed: at the top, the view has highlighted an asymmetric shape; at the bottom, it is visible the multiple mark inside the central hole.

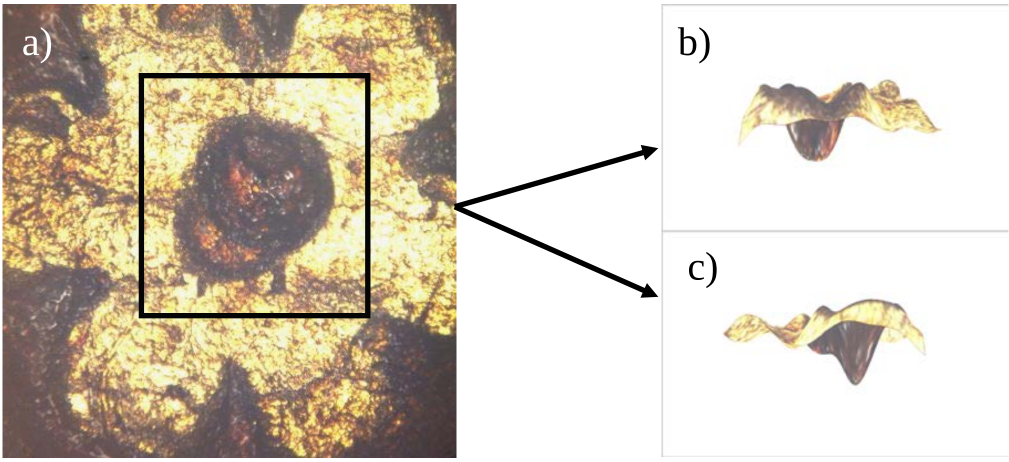

Fig. 6a. Hexa rosette mark with a defected central hole. Fig. 6b, c two views of the same central part of a hexa rosette mark 3D reconstruction.

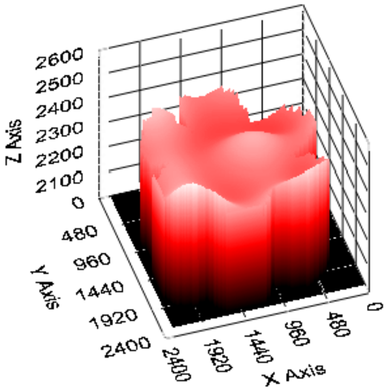

Fig. 7. 3D reconstruction of a hexa rosette punch tip tool.

In the framework of authentication, it is useful to link the punch marks on a painting to a specific tool used by an author or more generally by one author's workshop. The 3D technology is the only domain in which this effort is easily managed, the punch mark surface can be "inverted" to build a model for the punch tool used. The model can make sense only if it is statistically representative of the punch marks. A preliminary analysis of the statistical occurrence of the same mark (identified by the same morphological features) was performed. To this goal, the central hole diameter, punch depths and flower dimensions were measured for several hexa rosette marks. The mathematical information under the 3D surface was coherently inverted in order to obtain a 3D model of the hexa rosette punch (as depicted in Figure 7).

This operation has been carried out also for the third type of punch marks: the penta rosette [Frinta 1998 b]. It has more elaborated petals than does the hexa rosette; the flower is inscribed within a 3.7-4 mm circle with a central hole of less than 1 mm, and the punch mark depth ranges from 150 to 250 microns. It has been also noticed that the punch mark seems to have collapsed in the central part (Figure 8a). This effect, which was probably due to a progressive shrinking of the underlying preparation of the painting along with that of the wooden substrate, was mathematically considered in the 3D punch tool model (Figure 8b).

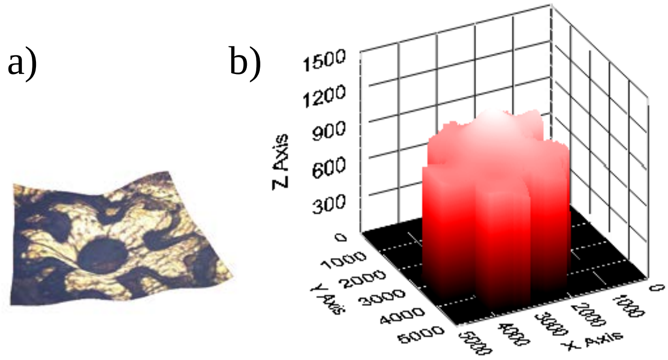

Fig. 8a. Penta rosette punch mark. Fig. 8b. The corresponding 3D tip tool.

4. DISCUSSION

The first punch mark group (simple circles) due to its general shape is used to address observations on the engraving curvature. No comprehensive list of all the circular punches actually exists that makes it possible, first of all, to distinguish convex and concave tools and, secondly, to associate them to a specific painter or workshop. The former feature cannot definitely be analyzed using traditional techniques such as macro photography as several other morphological features cannot be properly documented in this way. In the case of a convex tip (concave mark), the punch mark left on a surface in a photographic image is identified by a circle, the diameter of which can vary depending on the striking power of the punch. This leads to possible ambiguous cases: the same mark may be caused by a larger tip used with moderate force, or by a smaller tip used with greater force. A step forward, instead, is accomplished in the 3D domain, e.g. by measuring the punch mark curvature, the two situations could be discerned. This information could help identifying a painter who regularly used a particular punch size and striking force. The situation is reversed in the concave case: the punch tip is shaped in order to leave two concentric circles, the diameters of which are constant independently of the striking force used. Where these marks are sufficiently separated, no identification problems can arise; in the case of dense iterative concave punching [Frinta 1965], however, 3D analysis can easily distinguish features of overlapped marks. To this end, we have extracted profiles in an overlapped zone (as shown in Figure 9). As stated above, a weaker mark depth was found (on average, a few tens of microns, as compared to 100 micron for a non-overlapped mark, as in Figure 4b). This is clarified by observing the two dashed lines of Figure 9, which simulate a single punch mark repeated in order to achieve the granulated effect. Similar results were obtained with other profiles extracted in the same region.

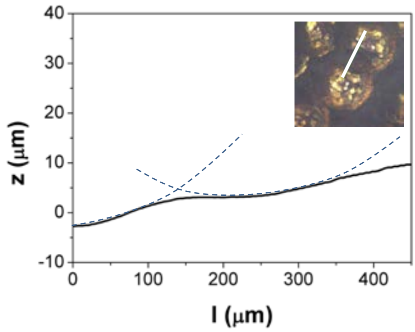

Fig. 9. A profile extracted from the 3D reconstruction of partially overlapped concave marks. Two dashed lines have been superimposed in order to simulate the repetition of a single mark.

The other two groups, namely the hexa and penta rosettes (essentially, a flower with a number of petals), were selected due to their more complex structure, and appeared to be suitable for authentication purposes. In these cases the potential of the 3D imaging approach can be demonstrated by extracting morphological features such as shapes and depth profiles from 3D data. In this way several aspects of the punching process (sliding and bouncing effect) can be introduced, and the presence of a defect in a punch tool can be identified as a specific marker for authentication purposes. In Figure 6 it has been framed the 3D reconstruction of a particular hexa rosette in which a defect appeared in the central hole. We have first considered this fact to be an occasionally bad mark, and explained it as a hesitation in the striking process. This could occur in several ways, depending on the number of hits. If the mallet wrongly hit the punch once, the tool could skid on the gilded surface, but this phenomenon would not substantially alter the resulting mark. On the contrary, only a multiple strike (tool bouncing) could considerably modify the mark shape: in the present case, we refer to both the central hole and the six petals. In the 3D domain, by taking advantage of eccentricity measurements and depth profiling, it is possible to separate the bouncing and the sliding effect. For this aim, in Figure 6 two different views of the same reconstruction have been presented. It is interesting to note that a multiple border has been observed only in the central part of the mark: on the contrary, the petals around the hole are clearly marked without a multiple border. In our opinion, these two issues could not be compatible with both the sliding and bouncing cases. In Figure 10 an asymmetric profile extracted from 3D data is presented, and superimposed in two possible positions (A, B) assumed by the sliding punch. The punch was stroke on the surface in a slightly angulated manner, and during the mallet hit, the punch slid from position A to B, thus creating the smooth profile shown in Figure 10. In this picture, however, the multiple mark of the central hole is not justified.

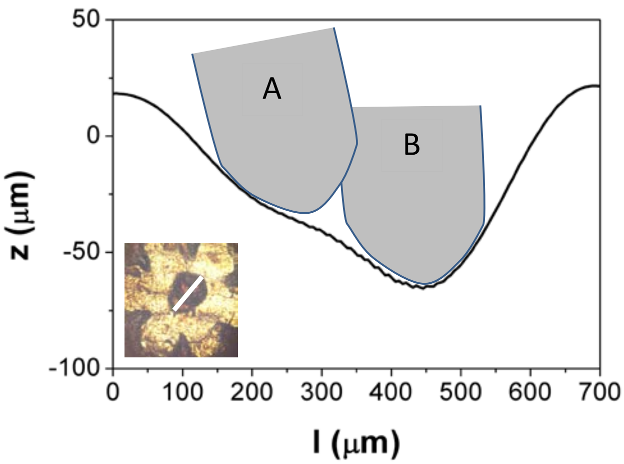

Fig. 10. Two possible positions assumed by a sliding punch in replicating the asymmetric profile.

The bouncing effect could explain the multiple mark, but not the smooth profile of Figure 10, because it is likely to be step-like. This hypothesis has been corroborated by calculating the eccentricity of the two circles in the central hole. A discrepancy of more than 30% between the bigger circle (less oblate because of a small eccentricity corresponding to the B position) and the smaller circle (A position) was found. This is compatible within the framework of the bouncing effect. The tilted punch tool had produced a smaller, more oblate and shallower mark (A); as it slid over the surface, a small rotation had made the tool and the gilded surface orthogonal. In this case, the punch tool had produced a larger hole that was less oblate and deeper. Moreover, both the sliding and bouncing should have produced effects also in the borders of the petals. As there is no evidence of either a sliding or a bouncing effect, the scenario should be changed. We have observed in other hexa rosettes the multiple mark in the central hole with single borders of the petals, see e.g. the two examples presented in Figure 11. One may legitimately conclude that this is not a mistake during the punching process, but that the tool itself has an imperfect surface. The hexa rosette punch tool used in this painting could therefore be univocally identified by its defect. Moreover, we observed a defect also in one of the six petals. Both these anomalies have been evidenced with arrows in Figure 11. This suggests 3D digital microscopy could help to solve certain authentication problems. Panel paintings were decorated using a number of similar punch motifs, which makes their association to a specific author or workshop very difficult and unreliable. Conversely, the possibility to characterize the same marks in different painting considering the presence or absence of defects offers a way to solve ambiguous cases of attribution. It is worth to consider that punch tools were produced from iron stock [Skaug 1994] through a fine engraving on its tip, which make them not replicable and therefore any profile defect can represent a uniqueness mark.

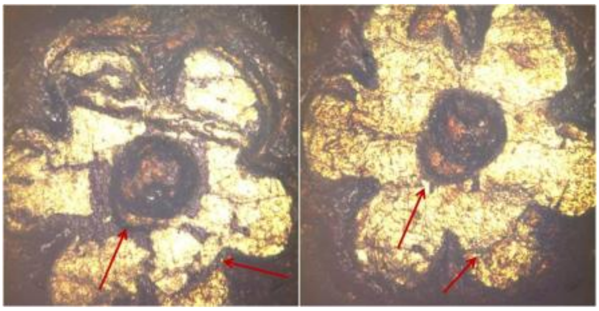

Fig. 11. Two different hexa rosette punch marks with a multiple central hole. The arrows indicate the punch marks defects.

5. CONCLUSIONS

The results reported demonstrate the capability of the 3D device and elaboration code developed for classifying and recognizing peculiar features of punching on medieval panel paintings. Portable 3D systems are truly attractive for archaeometrical applications. Due to their exclusive combination of handiness and wealth of morphological information, in the present framework, they can be considered as a valid substitute for commonly-used 2D imaging techniques.

The quantitative measurements of punch depth and the discovery of unique features of punch tooling processes reported in the present study, provide evidence of the significant potential of the technique. Three punch mark categories were measured: a simple circle, hexa and penta rosettes. The former is appropriate for morphological characterization in terms of shape and depth. Convex and concave punch marks were compared. In a problematic zone such as that of granulation (densely repeated punch marks), the proposed device was allowed identifying single punch marks even if these partially overlapped with their neighbors. The results achieved for the hexa rosette provide a meaningful example of anomalies attributable the punching tool. In particular, a multiple central hole has been interpreted as a defect of the punch tip, rather than a striking mistake (sliding or bouncing effect). This analysis can open new possibilities in authentication studies. The identification of the same defects in marks on different painting implies the presence of the same tool and therefore a clear relationship with that author or workshop could be established.

Finally, 3D reconstruction of the punch marks models for the tip tools by reversing the 3D relief was performed.

In the future, we plan to extended the investigation to other punch mark categories, while from the technological standpoint future efforts will be aimed at improving the optical system, in order to frame larger areas (of up to 1 cm).

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