3D Digital Imaging for Study and Semi-Automatic Matching of Ancient Sicilian Bronze Seals

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In the last decade, epigraphists have begun to show a new interest in signacula, a kind of seals used to identify soldiers (as the modern “dog-tags”) or even civilian goods. Signacula are a class of artifacts for a long time neglected. This has brought numerous contributions devoted to the different regional contexts, along with reflections on methodological questions, not to mention the momentum towards the digitizing of a corpus which counts at least 3.500 pieces. These artifacts have a great potential in providing information related not only to the economy and to the administration of the “res” (i.e., public and private affairs, as Romans intended), but also about the profile of the signacula holders. In this scenario, the Sicilian context proved to be particularly significant due to the presence of several seal impressions on mortar in the Late Antique cemeteries of Siracusa: a unique example in Sicily and an extremely rare one in Italian archaeology. This inspired a specific research question: it is possible to identify unequivocally a signaculum through its impression? And then, what are the implications for archaeological research? The aim of this contribution is to establish a protocol for semi-automatic matching between 3D models of seals and 3D models of impressions. This survey may open the way to the creation of a virtual edition of signacula augmented with 3D models of both seals and prints. We believe could be particularly meaningful to embed a method of seals and prints comparison in a digital collection of this kind. Furthermore, a research agenda may include the design of a machine learning algorithm for matching of 3D meshes.

Key words:
Signacula, Epigraphy, 3D digital imaging, Sicily, Catacombs.

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INTRODUCTION

The present contribution stems from a wider research concerning ancient bronze seals in Sicily. In fact, despite the growing interest in signacula over the last decade [Buonopane and Braito 2014], our actual knowledge of Sicilian seals still remains underdeveloped. A first succinct and partial cataloguing was arranged by Giacomo Manganaro in 2006 [Manganaro Perrone 2006]. The Sicilian finds – about 60 signacula and a dozen impressions left by seals on mortar in burial contexts confirm the great potential of these artifacts to provide information related not only to the economy and to the administration of the “res” (i.e., public and private affairs, as Romans intended), but also about the profile of the signacula holders. An accurate survey of images, forms and textual content of the seals may give

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insight on ethnic, cultural and social panorama of the Island. In 2015 a preliminary survey campaign took place into the repositories of the Sicilian museums, starting from the Museo Archeologico Regionale “Paolo Orsi” and the Antiquarium of the Pontifical Committee of Sacred Archaeology, both in Siracusa. The finds from Siracusa are particularly significant, by virtue of the presence of several impressions on mortar: a unique example in Sicily and an extremely rare one in Italy, where Rome seems to be the only comparable case [Ferrua 1986]. The relevance of the impressions is determined by their contexts of provenance (Late-Antique “hypogea” (i.e., underground temples or tombs) and common cemeteries of the Christian community), unlike the seals, for which only in very few cases it is possible to determine the origin. Even more difficult is the establishment of their chronology because of their long duration of use and the limited variations in shapes and paleography. Among the Sicilian signacula, scattered around various private and public collections, we have consistent evidence of their provenance for only 7 cases, which range from Palermo to Selinunte, Agrigento, Camarina, Comiso, Capo Schisò, Palazzolo Acreide and Siracusa [Manganaro 2006].

PROPOSED PIPELINE

Due to the difficulties in producing a satisfactory photographic documentation of seals and in order to preserve copies of the fragile and perishable impressions, a scanning campaign on some finds, selected among the most readable, has been started, using a NextEngine 3D triangulation laser scanner (Fig. 1). The NextEngine is usually employed for digitization in which a high level of detail is required; major details are given in Section 2.3.

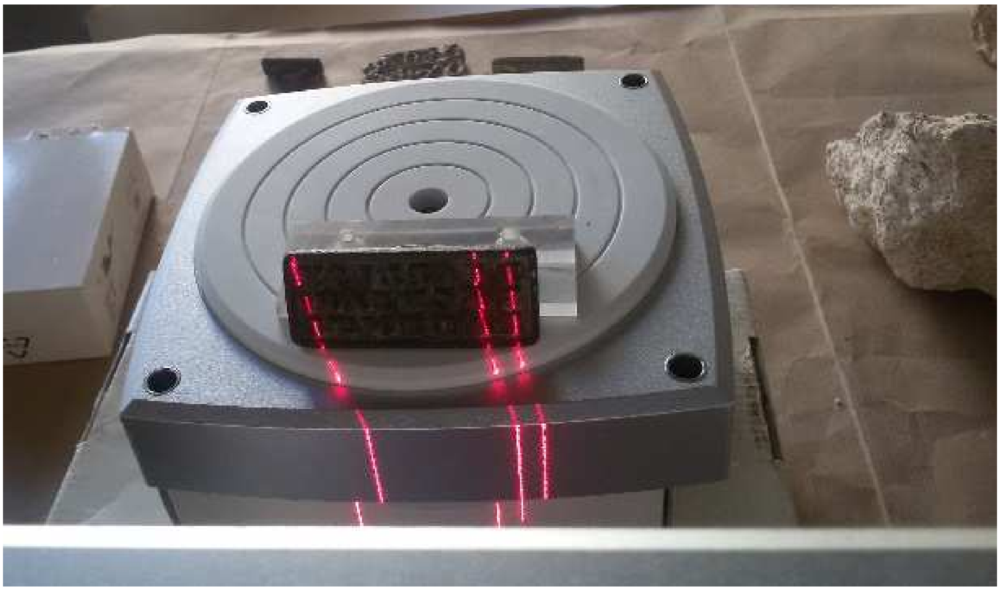

Fig. 1. 3D scanning of a signaculum via NextEngine triangulation laser scanner.

Given that the use of 3D documentation will bring effective results in terms of improved readability of signacula and impressions, a specific research question has been inspired by the Sicilian case: is it possible to identify unequivocally a signaculum by its impression? Although seals were produced using a matrix, they cannot be properly thought as results of a mass production because of their close relation to the owner, even in case of signacula in multiple copies which are identical or with few variants. Moreover, because of its function, the seal - not by accident in bronze - was meant to endure a long-time use, sometimes as long as the lifetime of the owner; and it was therefore subject to wear and tear effects which in some cases could have left distinctive signs on the artifact. For these reasons it may be extremely advantageous to elaborate an identity card of bronze seals via the analysis of detailed 3D models, and to improve matching cases between artifacts and impressions, in order to better identify context of provenance and chronology of the seals. The aim of this contribution is to establish a protocol for a semi-automatic matching between 3D models of seals and 3D models of impressions. We employed several softwares for different steps in the pipeline, including MeshLab (CNR-Italy) for pre-processing, ZBrush (Pixologic) to maintain original details of meshes and also to create manifold meshes for 3D printing. The pipeline is shown in Fig.2 and detailed in the following.

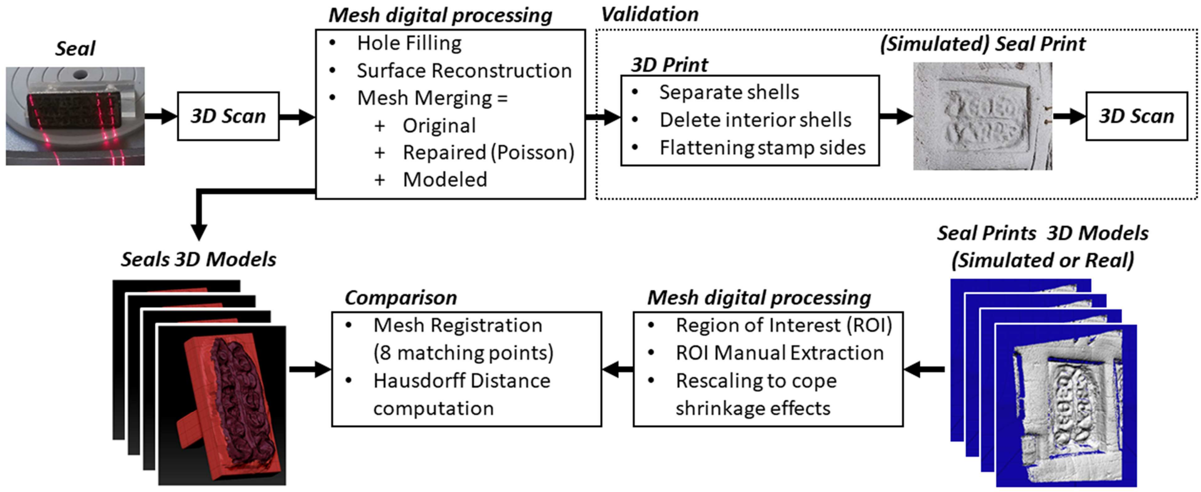

Fig. 2. Pipeline of the proposed method for seals and seal prints 3D models comparison.

3D Printing Replicas of the Seals

The original 3D scan meshes of two digitized seals (Inv. SN2 and 16191, simply reported as seal 1 and seal 2) were imported to MeshLab (CNR-Italy) and subject to pre-processing (Fig. 3) [Cignoni et al. 2008]. The holes were filled using the filter Surface Reconstruction: Poisson, with the settings suggested for a high definition reconstruction: Octree Depth equals to 10, Solver Divide equals to 8, Samples per Node equals to 20 and the default Surface Offsetting. Using Poisson, we introduced an error by generating missing parts.

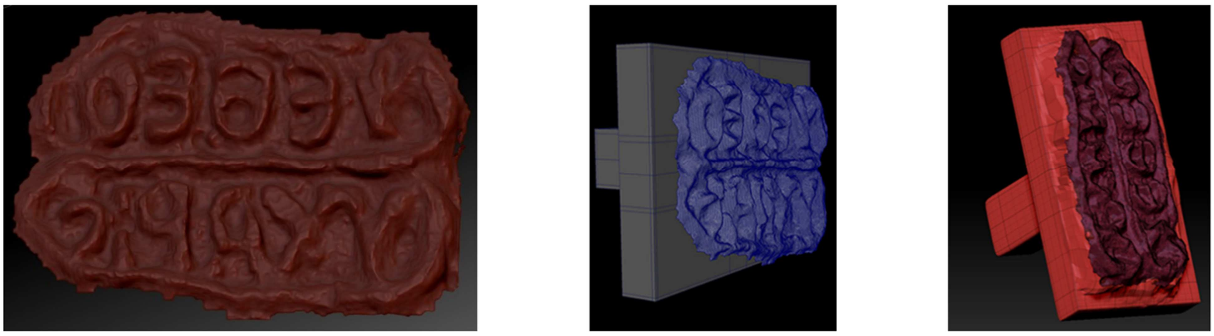

Fig. 3. Preprocess of the 3D mesh of a seal. Original and repaired meshes merged together in ZBrush (on the left). Digitized seal modeled in Maya (in the center). Stamp fill in ZBrush (on the right).

However, this error is negligible, as non-sampled areas are very small. Then, the repaired mesh was imported to ZBrush (Pixologic). In ZBrush the original scan was applied as a subtool to the repaired mesh, and the two were merged. This was done to capture as much of the original scan data as possible. Indeed, Poisson may have dropped some detail, hence in this way we restore it. The merged mesh was then made into a unified skin and exported as an OBJ file. The new OBJ mesh was imported into Autodesk Maya, where we created a polygonal model for the seal, and sized it to fit the mesh. When that was completed, we exported out of Autodesk Maya and imported the modeled seal back into ZBrush. Using ZBrush we filled and fit the seal so that there were no gaps to ensure that the post-processed mesh was a 3D printable manifold surface. Finally, the two parts of the modeled seal were merged and a unified mesh generated.

The printing process began by importing the merged mesh into MeshMixer (Autodesk). In MeshMixer we separated shells and deleted the interior meshes. We also used planar cut to flatten the stamp sides for easier printing. We exported the final stamp out of MeshMixer as a .STL file for printing (Fig. 4). The .STL was then set up for printing on both a FlashForge – Fused Filament Fabrication (FFF) and Formlabs Form 2 Stereolithography (SLA) printer. The printers were set to a layer height of 0.1mm with 10% infill for the FlashForge printer and layer height of 0.5mm with 100% infill for the Formlabs printer. We used two different printers, respectively able to print in plastic and resin, in order to investigate how many differences may rise from similar but not equal prints.

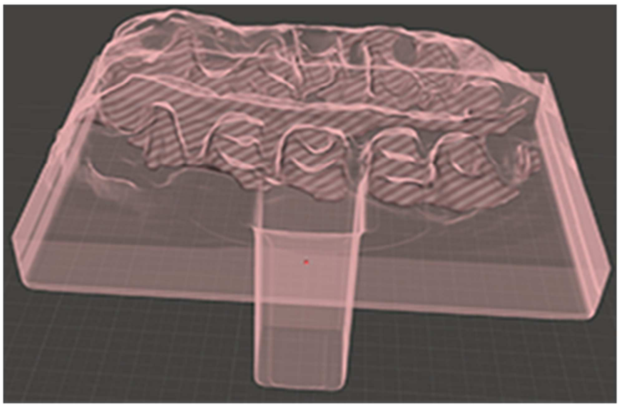
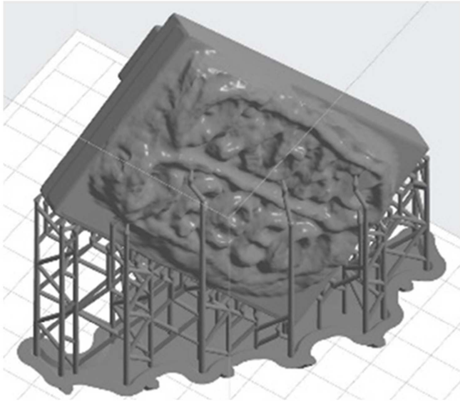

Fig. 4. 3D Printing process. Separating and deleting inner meshes for final (shown on the left) and Form 2 SLA 3D Printing software with STL model (shown on the right).

Creation of realistic print replicas

We prepared a mortar as a mixture of gypsum and sand, with a proportion of 50:50. We chose this ratio as it is proved to be worthwhile in order to obtain a mortar that is not much sticky and has a reasonable required time to dry. We stamped the seals in two cases filled with mortar (Fig. 5), applying a steady movement ensuring that the print replicas look realistic. Hence, we may distinguish three prints for case A (seal 1 replica in plastic not fitted with a modeled mesh, seal 1 replica plastic fitted with a modeled mesh, and seal 1 replica in resin) and four for case B (seal 1 replica in plastic fitted with a modeled mesh, seal 1 replica in resin, seal 2 replica in plastic, and seal 2 replica in resin).


Fig. 5: Cases A (shown on the left) and B (shown on the right) filled with mortar. On the upper part of the images seals are shown, while on the bottom part their related print replicas are clearly visible.

Digitization through 3D scanning of the print replicas

The digitization of the print replicas was carried out with two different 3D scanners: NextEngine and Sense. The NextEngine is a 3D laser scanner with a resolution of ±0:1mm in Macro Mode [NextEngine Website 2017], while the Sense 3D scanner has a resolution of ±1mm [Sense Website 2017]. Notice that the resolution is defined as the minimum dimension distinguishable by the scanner, hence the lower value the more accurate the scan. The NextEngine is usually employed for digitization in which a high level of detail is required. The Sense is based on structured light and thus scans faster compared to the NextEngine, but as a result the final mesh will have a lower quality. We employed both of them with the aim of comparing the meshes obtained from these two different sources and stating if it is possible to employ low cost handheld scanners for the scope of the topic presented in this paper. The acquisition with the NextEngine has been conducted with the following settings: single scan, highest quality, macro mode. Each acquisition required almost 3 minutes. Performing a single scan for each print replica results in final meshes that have some missing parts (Fig. 6). Multiple scans could have covered this missing data, but in this case a manual alignment of the scans would have been required instead. We adopted the single scan approach, in order to minimize the error produced by manual alignment. In this way, the only required alignment is the one needed for the comparison between the meshes of the seal and the print replica. The acquisition with the Sense 3D has been conducted with the standard settings. The scans were performed using the Sense 3D with a handheld approach and keeping an average distance of 30cm (the minimum possible distance for this device is 20cm). Each acquisition required almost 20 seconds.

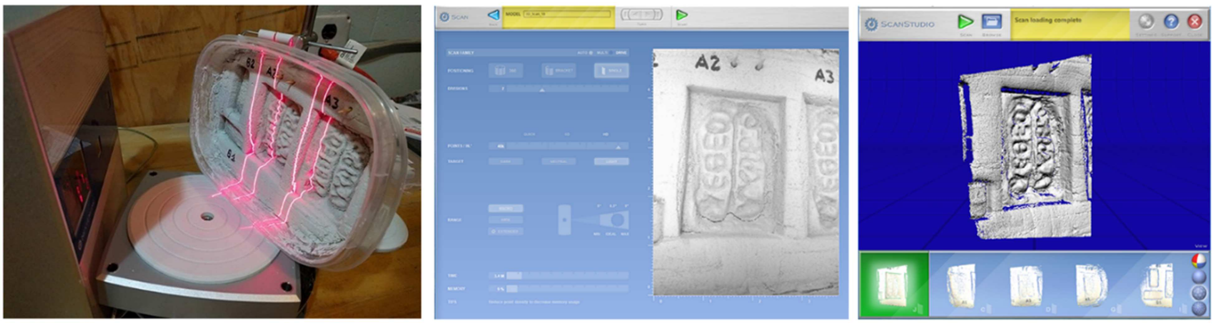

Fig. 6. 3D scan with NextEngine. Physical setting of the 3D scan (on the left). Acquisition settings of NextEngine (on the center). Example of digitized print replica after 3D scan through NextEngine (on the right).

Comparison between 3D model of the seal and 3D scanned mesh of the print replicas

Once the print replicas were acquired with the 3D scanner, we first define on the mesh a region of interest (ROI) around the print replica, removing the surrounding geometry. We process the meshes on MeshLab [Cignoni et al. 2008]. The ROI is manually defined through the Select Vertexes and Delete Vertexes tools. It was seen that the print replicas are smaller than the seals. This is due to autogenous drying-shrinkage phenomena that are very common in materials like concrete and gypsum [Yang et al. 2005]. For the same phenomena, the surface of the mortar may be cracked in some parts. We empirically measured this shrinkage on the mortar used in our experiments comparing several shrinking factors, properly from 0% to 15%, as suggested [Yang et al. 2005]. We found that the shrinkage affecting our seals is approximately of the 5% of the initial size. Hence, every mesh of the print replicas is rescaled using a scaling factor equal to 1.05 in every dimension. In order to compare the ROI with the 3D model of the respective seal we emulate the physical action of fitting the model and the print together. This procedure of physical fitting is usually difficult to be achieve due to various factors, such as shrinkage, missing parts or unknown orientations between seal and print. The digital fit of the meshes is done with a manual alignment tool (for pre-alignment) and Iterative Closest Point (ICP) procedure (for final alignment) through selection of points that look very similar in both models, known as Mesh Registration. The search for these kinds of matching point is more reliable compared to the process of manually fitting the meshes together. Potentially, just 3 points are needed for this alignment, but if more points are specified then alignment will be more accurate. In our experiments we selected 8 matching points for each alignment (Fig. 7).

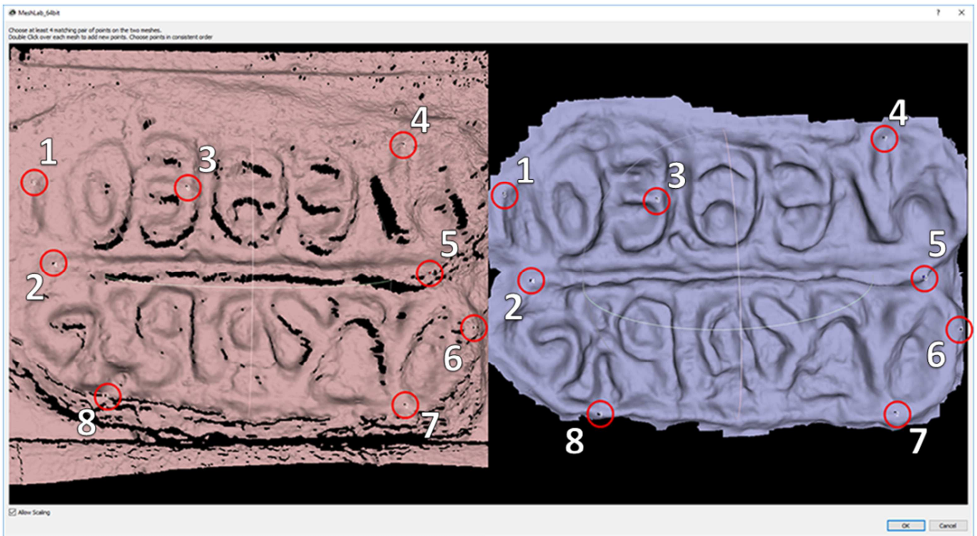

Fig. 7. Manual alignment in MeshLab environment (matching points have been labeled and highlighted with red circles to make them more visible).

Where it was possible, we preferred points on the boundary of meshes as in real cases details in the middle are often deteriorated and less reliable, while the silhouette of a seal is more clearly distinguishable. Indeed, it is easier to say that a circular print cannot be made by a rectangular seal, even if details in the inner part may be very similar. Then, we apply the filter Sampling - Hausdorff Distance between the ROI and the mesh of the seal [Winemiller et al. 2018; Allegra et al. 2017; Armstrong et al. 2018]. The Hausdorff distance is defined as the set of Euclidean distances between paired points of two meshes. In MeshLab this distance is implemented through a sampling of the meshes, in order to obtain paired points [CRS98]. The result of the distance computation is named in MeshLab Quality Vertex and can be visualized through the Colorize by Vertex Quality filter. It is also possible to compute and visualize a histogram of the Quality Vertex values. One can expect that two meshes that are very similar should obtain a histogram with a peak in the very low-valued bins. In Meshlab a jet color palette is used to represent the normalized Quality Vertex values, with red and blue colors used for high and low values, respectively. We recall that higher Quality Vertex values are obtained where Hausdorff distance is lower, and viceversa. The comparison between 3D models of the seals and 3D scanned meshes of the print replicas is shown in Fig. 8 and 9. However, the Sense 3D scanner was not capable of acquiring the small details on the surface of the print replica of our second seal, hence we were not able to compute the Hausdorff distance of these meshes.

Discussion about the meshes comparison and Hausdorff distance

There are several works in literature employing a similar pipeline w.r.t. the one proposed in this work [Remondino 2011; Gaiani et al. 2016; Russo and Manfredini 2015; Allegra et al. 2016; Winemiller et al. 2018; Allegra et al. 2017; Armstrong et al. 2018]. We employed this kind of distance in order to assess what are the parts of a print that are more similar to the respective seal. The way in which the distance should be used is more oriented to a visual evaluation of the obtained Quality Vertex values. Indeed, if the whole mesh has a reddish colorization, then one is able to assess that the two compared meshes are alike (i.e., the match between seal and print is very good). However, the Hausdorff distance should not be used to ensure a match without any other cue. Instead, it should be used to reject clearly mismatch, since it is very unlikely that mismatching prints and seals could obtain the same low-ranked distance values, as the one shown in the reported experiments. For instance, the last model of seal shown in Fig. 9 obtained a nice Quality Vertex colorization of the meshes and some low-ranked values in its histogram. However, it seems difficult to assess from a match of this kind if it should be treated as a correct match or a mismatch, but it is possible to state that there is a partial match, at least. In Fig. 8 and 9 we have shown the Hausdorff distance values using histograms colored with a jet colormap (from red to blue colors). All the reported histograms show only the values within the range from 0 to 3, with 256 bins. The width of the bins is normalized between 0 and 3142 (the highest number of elements in a single bin recorded in our experiments). Firstly, we stress that the highest Hausdorff distance was computed for meshes acquired by Sense 3D. This is an expected behaviour due to the low resolution of the scan (±1mm). The histograms of the meshes acquired with Sense 3D compared with the ones of the NextEngine are wider and with a lower number of elements in the low-ranked bins. Secondly, we notice a slight difference between the seals printed in plastic and the ones printed in resin. In particular, the resin seals are stickier and when used in the process of making print replicas a bit of mortar remains attached on them. This results in print replica being less accurate. It should be worthily noted that stickiness of replicas printed in resin could be an issue related to insufficient post-processing to remove excess resin on the surface left over after printing. Indeed, SLA modelling should exhibit higher accuracy compared to lower FFF model due to absence of filament size on layer thickness. Another external factor to properly account in our validation procedure is related to the way imprints are applied: the pressure, the direction of application and the precise mix of the mortar, although controlled for most of these, may still be affected by human error. Finally, Mesh Registration represents another source of external error. We performed it using 8 matching points, carefully selected to obtain the best possible mesh registration. However, error may be still present and in a well assessed procedure more registrations may be required to assess a robust estimation through Hausdorff distance.

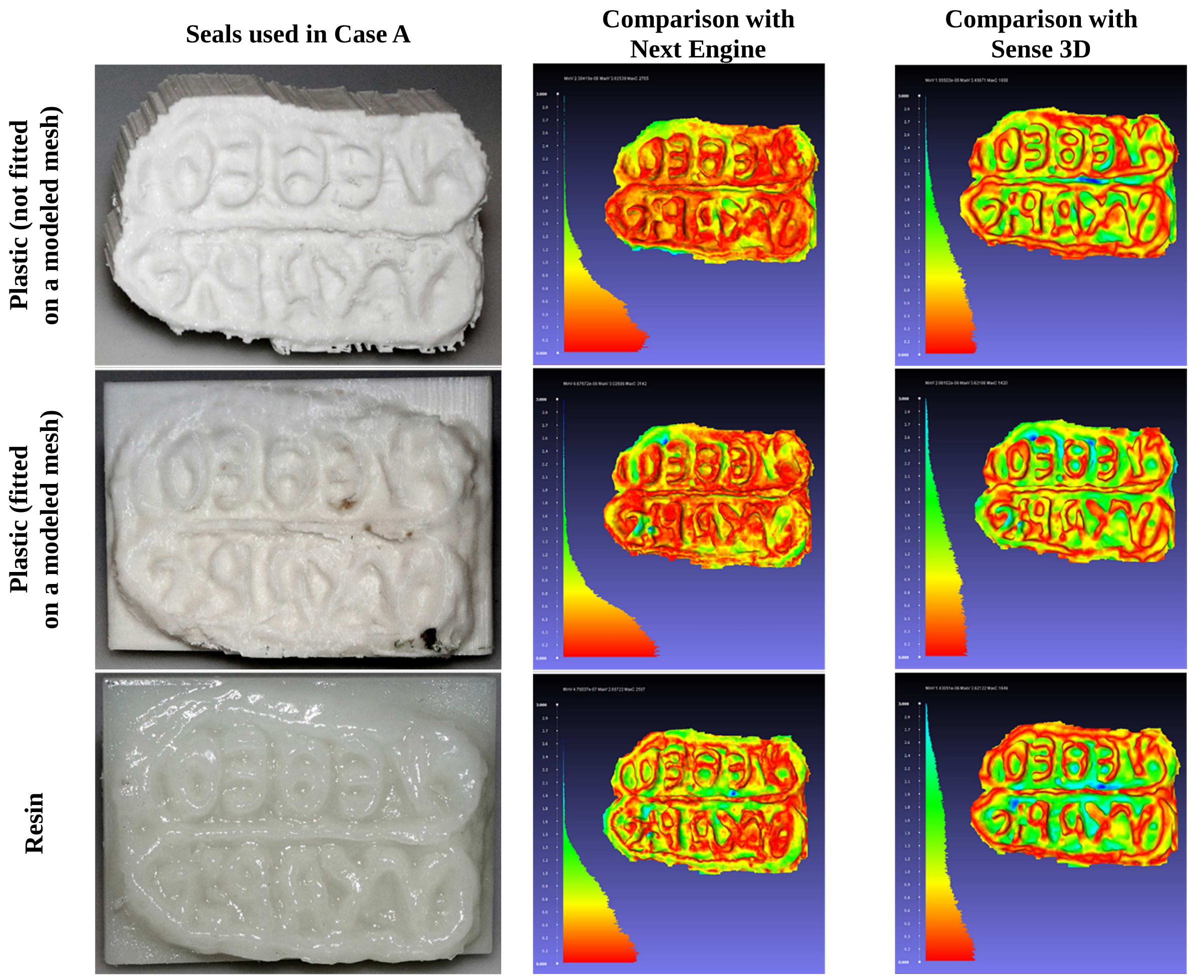

Fig. 8. Computation of Hausdorff distance on print replicas in case A. Photos of the seals are shown in the first column, while the Hausdorff distance between the model of seal and digitization through NextEngine and Sense 3D are shown in the second and third columns, respectively. All the histograms have the same fixed setting: only the Hausdorff distance values from 0 to 3 are shown, with 256 bins; the width of the bins is normalized between 0 and 3142 (the highest number of element in a single bin for this experiments).

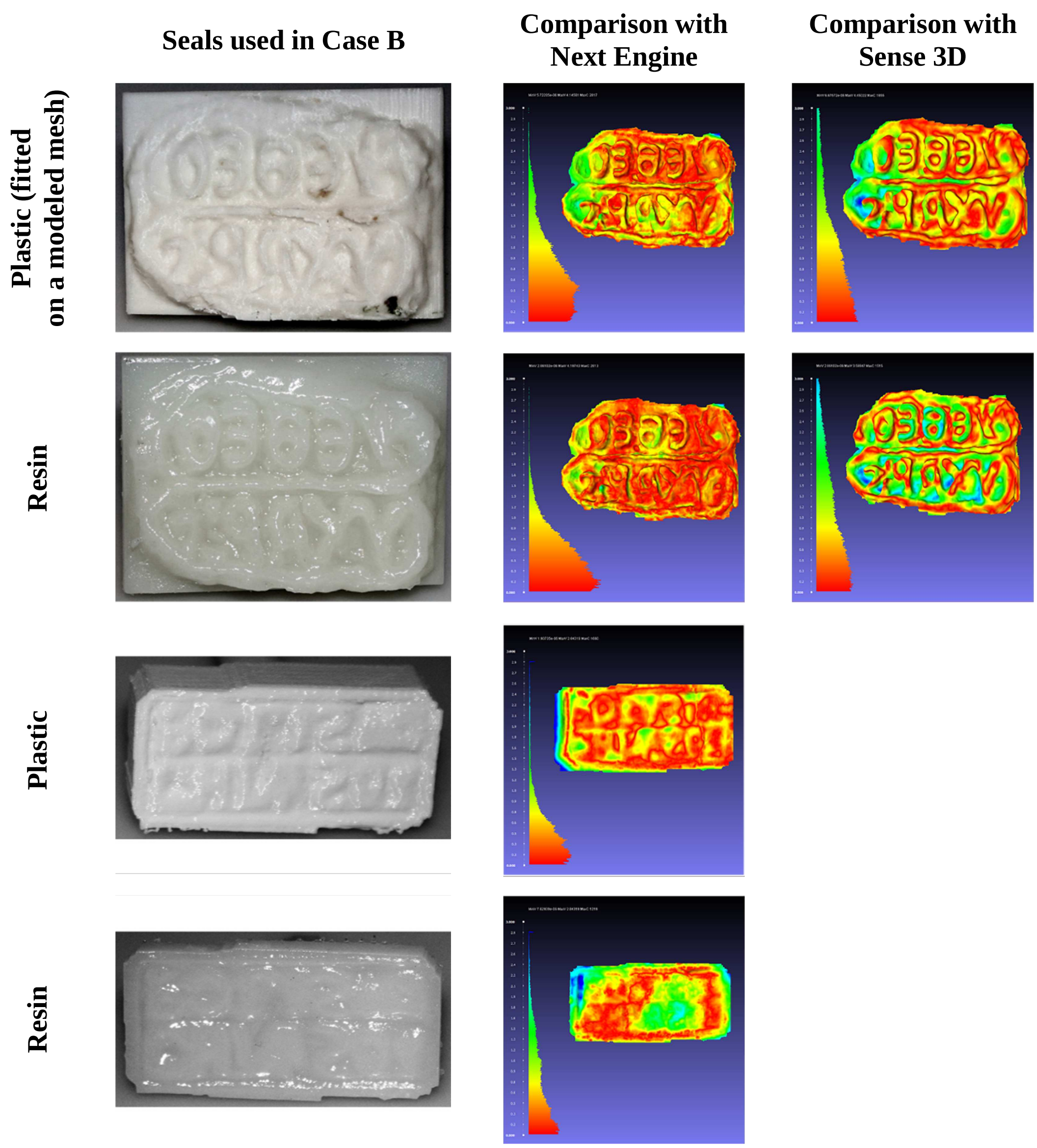

Fig. 9. Computation of Hausdorff distance on print replicas in case B. Photos of the seals are shown in the first column, while the Hausdorff distance between the model of seal and digitization through NextEngine and Sense 3D are shown in the second and third columns, respectively. The last two seals have not been compared with Sense 3D as the digitized meshes have too low quality. All the histograms have the same fixed setting: only the Hausdorff distance values from 0 to 3 are shown, with 256 bins; the width of the bins is normalized between 0 and 3142 (the highest number of elements in a single bin for this experiments).

CONCLUSION

We presented a pipeline for comparing 3D models of digitized ancient Romans seals, called “signacula”, with 3D models of seal prints. The whole pipeline is composed by several steps, including different mesh processing methods applied on the meshes of both seals and prints, and a comparison strategy relying onto Hausdorff distance. We validated our pipeline using two signacula. Artifacts have been 3D scanned and meshes were processed to obtain a smooth surface with enough details. Then, mockups were 3D printed in two different materials, properly plastic and resin, in order to investigate how many differences may rise from similar but not equal prints. These 3D printed replicas were used to simulate signacula prints, that have been 3D scanned and compared with the seal models.

Comparison is based on Hausdorff distance. The aim was to establish if prints were actually made by employed seals. We found that Hausdorff distance should not be used to ensure a match without any other cue. Instead, it should be used to reject clearly mismatch, since it is very unlikely that mismatching prints and seals could obtain the same low-ranked distance values, as the ones shown in the reported experiments.

The archaeological implications deriving from the application of such innovative digital approach for the study of Roman signacula are rather significant. First of all, the possibility of associating a signaculum to a precise archaeological context of use or reuse and to a territory allows the full use of the data provided by the artifact, significantly reducing the approximation determined by the great mobility of signacula, both in antiquity and through the modern antique market. With regard to the Sicilian signacula, one of the first significant and unexpected results, albeit out of a modest collection of samples, was the confirmation of the prevalent use of Latin language and characters on the seals (49 on 59 signacula = 83%), corresponding to the same phenomenon on the impressions (7 on 9 impressions = 78%), in a region that throughout the Imperial age was mostly Greek-speaking. Certainly one of the future aims of the archaeological investigation is to extend the research to other categories of artifacts that can preserve impressions of signacula (such as amphorae and bricks), trying to map the distribution and the mobility of the seals via their impressions. However, the test of the protocol on two specimens, even with promising outcomes, requires an extended experimentation period on a larger selection of artifacts. The creation of a virtual collection of signacula augmented with 3D models of both seals and prints remains an open option at the top of our research agenda. We believe could be particularly meaningful to embed a method of seals and prints comparison in a digital collection of this kind,

where becomes extremely important to design a machine learning algorithm for matching 3D meshes automatically in order to drop the manual exercise via the use of the Hausdorff Distance. In the future, we are planning to test and compare other technologies (i.e. RTI imaging) apart from the 3D scanning, which have been proved to be difficult for handling data and scanners can be expensive. Another promising method for further investigation is represented by the employment of image processing and visual feature matching techniques based on depth-maps, which may substitute the more complex machine learning approach.

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