3D HIGH-QUALITY MODELING OF SMALL AND COMPLEX ARCHAEOLOGICAL INSCRIBED OBJECTS: RELEVANT ISSUES AND PROPOSED METHODOLOGY

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ABSTRACT:

3D modelling of inscribed archaeological finds (such as tablets or small objects) has to consider issues related to the correct acquisition and reading of ancient inscriptions, whose size and degree of conservation may vary greatly, in order to guarantee the needed requirements for visual inspection and analysis of the signs. In this work, photogrammetry and laser scanning were tested in order to find the optimal sensors and settings, useful to the complete 3D reconstruction of such inscribed archaeological finds, paying specific attention to the final geometric accuracy and operative feasibility in terms of required sensors and necessary time. Several 3D modelling tests were thus carried out on four replicas of inscribed objects, which are characterized by different size, material and epigraphic peculiarities. Specifically, in relation to photogrammetry, different cameras and lenses were used and a robust acquisition setup, able to guarantee a correct and automatic alignment of images during the photogrammetric process, was identified. The focus stacking technique was also investigated. The Canon EOS 1200D camera equipped with prime lenses and iPad camera showed respectively the best and the worst accuracy. From an overall geometric point of view, 50 mm and 100 mm lenses achieved very similar results, but the reconstruction of the smallest details with the 50 mm lens was not appropriate. On the other hand, the acquisition time for the 50 mm lens was considerably lower than the 100 mm one. In relation to laser scanning, the ScanRider 1.2 model was used. The 3D models produced (in less time than using photogrammetry) clearly highlight how this scanner is able to reconstruct even the high frequencies with high resolution. However, the models in this case are not provided with texture. For these reasons, a robust procedure for integrating the texture of photogrammetry models with the mesh of laser scanning models was also carried out.

1. INTRODUCTION

Nowadays, digital technologies increasingly influence archaeological research, offering an efficient way to represent the real world, allowing to variously manipulate and evaluate measurements, compute statistics and transmit data and results to a worldwide audience (Zubrow, 2006). In particular, 3D modeling of archaeological finds can rely on several established techniques and methodologies, such as photogrammetry or laser scanning (Remondino et al., 2005),(Ravanelli et al., 2016).

Even if these methodologies are well-defined in terms of principles and general procedure, new technical solutions have to be found from time to time to fine-tune the results, depending on the peculiarities of the specific case study. The problem of 3D modeling of inscribed archaeological finds (such as tablets or small objects) shows this necessity quite clearly, because it has to consider issues related to the correct acquisition and 'reading' of ancient inscriptions, whose size and degree of conservation may vary greatly, in order to guarantee the needed requirements for visual and machine inspection and analysis of the signs.

This paper aims at defining a robust procedure and technical solutions, also considering sensors and settings, to address the 3D reconstruction of inscribed objects, paying particular attention to the geometric accuracy and operative feasibility, in terms of required sensors and needed time. In particular, its main goal is to provide a knowledge basis for the activities which will be carried out in conjuction with a specific strand of the ERC Consolidator project entitled INSCRIBE - 'INvention of SCRIpts and their BEginnings', under the direction of Silvia Ferrara (University of Bologna) as PI (INSCRIBE, 2018a).

One of the INSCRIBE objectives is to produce the first digital corpus of undeciphered scripts from the second millennium BC Aegean (Cretan Hieroglyphic, Linear A and Cypro-Minoan), which would involve hundreds of inscribed objects and would overcome the limitations of traditional databases. Indeed, standard corpora of inscriptions produced until now are usually based on black and white images of inscriptions and tend to omit the illustration of the whole objects, focusing only on the inscribed parts. Furthermore, the facsimiles (drawings made by hand) of the inscriptions often present imprecise or subjective transcriptions, producing an artificial normalization of the graphic forms of the registered signs.

3D models will represent the inscriptions in their whole entirety instead, allowing an objective analysis of the inscribed signs and overcoming the limitations and arbitrariness of the catalogues published so far, that have been the standard in the state of the art in Aegean studies.

Because of this, several tests were carried out on the following objects:

- a Cypro-Minoan inscribed clay ball replica;

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- a gypsum replica of a cuneiform tablet from Damascus National Museum;
- a gypsum replica of a cuneiform tablet from Ebla, Syria;
- a gypsum replica of a cuneiform clay tablet from Ugarit, Syria.

These objects differ in terms of morphology, size, material and script characteristics, thus they provide a significant test field for our experiments. Specifically, the 3D reconstruction was performed using both photogrammetry and laser scanning.

As far as concerns the first method, image resolution (therefore sensor specifications) was conditioned by the average size of signs (which is approximately few mm): macro lenses were supposed to be ideal for this purpose, because they have high resolving power. To overcome the problem of their limited depth of field (DoF) and to extend their sharpness area - avoiding any loss of quality due to diffraction (Gallo et al., 2014) -, *focus stacking* (Clini et al., 2016),(Kontogianni et al., 2017) was used. Focus stacking, which is implemented in several algorithms, open source and commercial software, leverages a sequence of images (representing the same subject from the same position) captured with increasing (or decreasing) focus length in order to obtain a single image with an extended DoF. In this work, Helicon Focus commercial software (HeliconSoft, 2018a) was used for focus stacking, while Agisoft Photoscan - based on *Structure from Motion* algorithm - was employed in the photogrammetric process.

For the laser scanning procedure, we used the ScanRider 1.2 model by VGER. This is a high-resolution laser scanner (see Table 3) based on structured light technology. It is not able to provide texture to 3D models, but the geometric complexity of the objects of interest suggested the necessity to rely on a scanner capable of reconstructing even the smallest of details (or high frequencies) with a high degree of accuracy.

This work focuses precisely on the strategies and practical background built during the experiments, carried out with several sensors and components, in order to guarantee an optimal data acquisition. In addition to this, an important result derives from the integration between photogrammetry and laser scanning, useful to apply photogrammetric texture on laser scanning 3D models.

The work is structured as follows: first, the peculiarities of each case study are presented; second, the tested sensors and their specifications are described. Third, the experimental setup, test settings and data processing are summarized, and finally the results are detailed and some conclusions are drawn.

2. CASE STUDY

The inscribed objects reconstructed in this work are characterized by high geometric complexity and different properties in terms of sign shapes, which have a significant influence over specific sensors to use, light conditions and experimental setup. The four replicas are shown in Figure 1. The clay ball diameter measures about 2.5 cm; the small size of this object makes it very sensitive to light variations and to lens properties. With regards to the three tablets, their approximate main dimensions are indicated in Table 1.

In general, the 3D models of all the objects required high accuracy and precision, in order to appropriately show the inscriptions. An important aspect to consider when trying to acquire the models of the tablets is that they essentially have two prevailing dimensions: because this study is functional to reconstructing their overall 3D shape, and not to produce 2.5D models, the edges have to be acquired with particular care, assuring an ideal overlap area between images for the photogrammetric process.

Tablet	length (cm)	width (cm)	thickness (cm)
from Damascus	9	7	4
from Ebla	7	6	2
from Ugarit	7	6	2

Table 1: Tablet approximate main dimensions

Megapixels	[pixel]	$8 \cdot 10^6$
Resolution	[-]	(3264×2448)
Pixel size	[μm]	1.12
Aperture	[-]	f/2.4

Table 2: iPad Air 2 rear camera specifications

3. TESTED SENSORS

Several sensors were employed during the tests. Besides the ScanRider 1.2 laser scanner, different cameras (the iPad Air 2 camera and a Canon EOS 1200D camera) and lenses were used to capture the images needed for the photogrammetric process.

Specifically, some photogrammetric tests were performed with the iPad Air 2 rear camera (Table 2). The camera parameters *ISO*, *EV* (exposure value, a combination of shutter speed and f-number) and *shutter speed* could be set by means of CameraPixels app (CameraPixels, 2018). The same app was fundamental to collect image stacks with this sensor, used in combination with an adequate macro lens (shown in Figure 2).

A second set of photogrammetric tests employed a Canon EOS 1200D camera, provided with a CMOS sensor of approximately 18 megapixels, whose size amounts to 22.3×14.9 mm (and crop factor to $3:2$). Moreover, three different lenses were adopted: a 18-55 mm lens (which was also tried in reverse mode, making use of a reverse lens adapter, that does not interfere with autofocus, necessary for focus stacking), a macro 100 mm lens and a YONGNUO F1.8 50 mm lens (all visible in Figure 3). The first lens was tested because it is the default one for all cameras, while the 50 mm one was considered an interesting solution because it is inexpensive and useful to reduce distortions (due to the fact that it is a prime - fixed - lens). The 100 mm lens was used to effectively set up macro photogrammetry (among its advantages, it allowed us to fix the reproduction ratio, which was set to 1:1 to avoid image distortions), whereas the reverse 18-55 mm lens was tried as a cheaper substitute of the previous one (Hogton, 2018). The camera parameters (ISO, focal length, shutter speed and aperture) could be set by means of Helicon Remote software, which allowed also to remotely control the camera and realize image stacks.

For the laser scanning, instead, ScanRider 1.2 implements the structured light technique through a DLP projector and a panchromatic (black and white) camera. The object must be placed on the automatic scanner turntable and is captured on all of its sides (Figure 4): indeed, the scanner allows to acquire different sides of the same object separately and to merge them at a later stage, by means of its scanning software SpaceRider.

ScanRider 1.2 allows to produce scaled 3D models of small objects (with a maximum length of 150 mm) with accuracy and precision depending on the selected scanning volume. In fact, ScanRider 1.2 can adopt three different scanning volumes, according

Figure 1: From left to right, the replicas of the tablet from Damascus, the tablet from Ebla, the clay ball and the tablet from Ugarit

	Volume 1	Volume 2	Volume 3
Volume maximum size (mm)	66 × 50 × 50	133 × 100 × 100	300 × 225 × 225
Object maximum size (mm)	66	133	150
Standard resolution (mm)	≤ 0.05	≤ 0.1	≤ 0.23
Precision (mm)	≥ 0.03	≥ 0.07	≥ 0.15
Mean error (mm)	≥ 0.01	≥ 0.03	≥ 0.05
Working distance (mm)	120	200	520

Table 3: Scanning volume specifications of the VGER ScanRider 1.2 laser scanner

Figure 2: Macro lens for iPad

Figure 3: 18-55 mm, 100 mm and 50 mm lenses for the Canon EOS 1200D camera

to the object size and complexity: the smaller the volume, the more precise and accurate the model results (Table 3).

4. DATA ACQUISITION AND EXPERIMENTAL SETUP

4.1 Photogrammetry

The experimental setup and the capturing scenario varied significantly from test to test, involving new strategies to solve the problems raised in the preliminary acquisitions.

For all the tests, the choice of the camera settings (both for the iPad and the Canon camera) followed some general rules, here summarized:

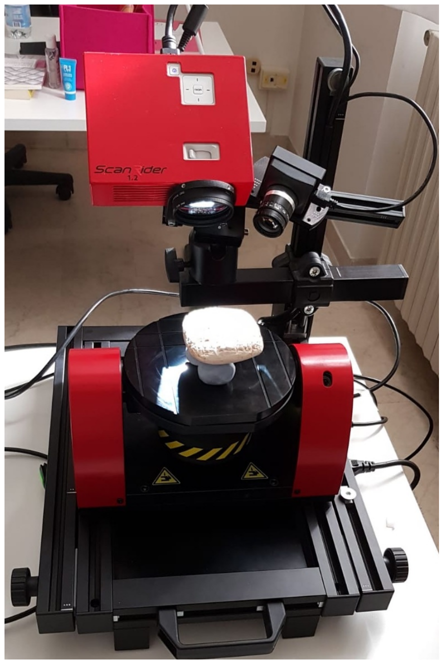

Figure 4: The ScanRider 1.2 by VGER in action

- ISO value was set below or equal to 100, adequate to good light conditions and small enough to avoid grain and noise;
- aperture values were never too high (going from f/2.4 - for the iPad camera - to a maximum, for the Canon camera, of f/13), to assure a sufficiently shallow DoF, suitable for such small objects;
- a medium value of shutter speed was always chosen (between 0.01 and 1s), based on the light conditions and sufficient to guarantee sharp images.

Some initial tests were carried out to check the feasibility of a simple and quick scenario: in fact, simplicity and speed of execution are a key aspect when acquiring huge amounts of 3D data from several inscribed objects. Because of this, the iPad was employed in these preliminary tests, since it is a very handy and commonly used device, thus allowing to perform quick acquisitions. Moreover, these preliminary tests allowed also to investigate the Agisoft Photoscan capabilities to process focus stacked images. In particular, three shoot sessions were carried out on the clay ball and on the tablets from Ugarit and from Damascus (tests C1, U1, D1 - see Table 4). To achieve the same simplicity and speed of execution, lighting conditions were not controlled specifically, relying either on sunlight or common artificial light only. In addition to this, as far as concerns the capturing scenario, the clay ball (C1) images were not acquired according to a predetermined scheme, thus image distribution in space was quite random, whereas in the other two tests (U1, D1) the acquisition was approximately regular, because the tablets were manually rotated, allowing to take images along circular paths around the object. In order to cover all sides of the objects and to avoid missing parts in the final models, the objects had to be rotated and turned upside down. Each change in orientation was accompanied by a background change, with the aim of avoiding erroneous matches during the image matching process (this procedure was repeated even if, in some cases, the background was out of image DoF, thus appearing blurry) (Mallison, 2018). Moreover, as far as concerns targets placed in the scene for marker collimation, two strategies were tested, but only the latter one proved successful: for the clay ball, a couple of rulers were included; for the tablet from Damascus, a DUPLO™ brick construction with known dimensions was used as a support and placed on a sheet of graph paper. The focus stacking technique was used (by means of the CameraPixels app) both for the tablet from Ugarit (U1) and the tablet from Damascus (D1), while it was not necessary for the clay ball (C1), completely included in the camera DoF.

Subsequently, the iPad camera was used for two additional tests, carried out on a more complex and supervised acquisition scenario. The same setup was employed for a second set of tests performed with the Canon camera, as described below.

As to the lighting conditions, two solutions were tested:

- in the first case, objects were placed inside a diffuser photo box, which provides quite uniform lighting by means of a row of LED lights and creates a neutral environment, particularly useful to the image matching process (tests C2, C3, C4, C5);
- in the other tests (C6, C7, U2, D2, D3, E1, E2), in addition to the diffuser photo box, a flash ring with a white filter was attached to the camera lens in order to get rid of the residual shadows.

Furthermore, instead of moving the camera around the subject, the sensor remained fixed (held by hand approximately in the same position in the case of the iPad or mounted on a tripod in the case of the Canon camera), whereas the object was rotated by means of a turntable. As regards the Canon camera, it was also connected through an USB cable to a laptop and controlled by means of Helicon Remote software, in order to avoid vibrations, thus preventing blurriness. The use of pieces of blue tack to glue the support to the turntable and the turntable to the base of the diffuser photo box made the whole system more stable to vibrations.

In order to cover all the sides, after having completed some shoot sessions of the first side, the objects were turned upside down and the support and background (if included in the camera DoF) were changed. Special care was paid to the acquisition of the edges of the tablets, ensuring enough overlap area between the images and making use of focus stacking to increase the number of tie points.

By means of DUPLO™ bricks covered with graph paper (used as support), it was possible to provide a scale to the models obtained from tests C7, U2, D2, D3, E1, E2.

In Table 4 more details concerning the dataset number, the number of images resulting from focus stacking, the acquisition time and the implementation of a scale are given for each of the 14 tests. The clay ball was involved in many of the tests carried out, because of its challenging uniform surface and small size.

4.2 Laser scanner

The clay ball and the tablet from Ebla were reconstructed using scanning volume 1, while the other tablets with volume 2. Before the tests, ScanRider 1.2 was calibrated: a separate calibration was performed for each of the two scanning volume selected. The objects were glued to the scanner turntable by means of pieces of blue tack. The superior and inferior part of every replica were reconstructed in two different scanning sessions and the resultant 3D models were merged by means of the SpaceRider software. The time required to conclude a complete 3D model was about 20/30 minutes, depending on the preselected scanning volume.

5. IMAGE PROCESSING

Before the photogrammetric process could effectively begin, image stacks had to be processed on Helicon Focus. The focus stacking method implemented in this software is based essentially on three parameters (HeliconSoft, 2018b):

1. *Rendering method* or focus stacking algorithm; there are three different algorithms: *method A* computes the weight for each pixel based on its contrast, after which all the pixels from all the source images are averaged according to their weights; *method B* finds the source image where the sharpest pixel is located and creates a “depth map” from this information (in other words, the algorithm operates a pixelwise search of the pixel with the highest contrast in a stack of images); *method C* uses a pyramid approach to image representation;
2. *Radius* defines the number of pixels around each pixel that are used to calculate its contrast;
3. *Smoothing* defines how the sharp areas (i.e. the areas with the highest contrast from the image stack) are combined.

We opted in all cases for *method B*, because, considering our case study, the images would not have sudden and frequent high DoF variations and because it was considered important to preserve the original colours and contrast. Small values of *Radius* (which was set to 3 pixels) and *Smoothing* (which was set to 4) were always chosen, after having checked the absence of halo in the computed images.

The photogrammetric process was carried out on Agisoft Photoscan; the same procedure was repeated for all the successful tests (i.e. those leading to a correct image alignment): first of all, the images were aligned with the desired accuracy. In particular, it is worth noting that the images were captured in such a way that an automatic alignment would be possible, in order to avoid to manually collimate some details on the objects. In this way, it is

Object	Sensor and lens	Test ID	Effective dataset	Images resulting from focus stacking	Time of acquisition	Scale
Clay ball	iPad - simple capturing scenario	C1	236	0/236	×	No
	iPad - complex capturing scenario	C2	246	71/246	×	No
	iPad with macro lens	C3	87	0/87	×	No
	Canon - 18-55 mm lens	C4	54	54/54	×	No
	Reverse 18-55 mm lens	C5	106	106/106	8h 20 min	No
	Canon - 100 mm lens	C6	64	64/64	∼ 2 h	No
	Canon - 50 mm lens	C7	80	0/80	19 min	Yes
Tablet from Ugarit	iPad	U1	52	52/52	22 min	No
	Canon - 50 mm lens	U2	74	29/74	50 min	Yes
Tablet from Damascus	iPad	D1	104	104/104	44 min	Yes
	Canon - 100 mm lens	D2	67	67/67	1 h 57 min	Yes
	Canon - 50 mm lens	D3	72	28/72	37 min	Yes
Tablet from Ebla	Canon - 100 mm lens	E1	121	121/121	3 h 5 min	Yes
	Canon - 50 mm lens	E2	61	23/61	48 min	Yes

Table 4: Effective dataset, images resulting from focus stacking, acquisition time per test and scale for each test

possible to contain the overall processing time as limited as possible, avoiding also to introduce subjective errors. Subsequently, the alignment was refined by automatically and gradually selecting and removing the uncertain tie points. The automatic point selection and removal were followed by a more precise manual selection. After that, when an adequate external scale had been provided during the shoot session, a minimum of 6 markers was detected (each one collimated on at least 4 images). Thereafter, the point cloud was densified with the desired quality. Finally, the mesh was generated and texturized.

Furthermore, the processing time was another key aspect to evaluate, in order to assess the best sensors in terms of operative feasibility. Because of this, the processing time on Agisoft Photoscan (the time required to focus stacking was negligible) was measured for all the successful tests, and it is summarized in Table 5. The whole photogrammetric process was always carried out on a Mac Pro, having a 3.5 GHz 6-Core Intel Xeon E5 processor, a 64 GB 1866 MHz DDR3 memory and an AMD FirePro D300 2048 MB graphics card.

6. RESULTS

6.1 Photogrammetric models

Some tests were not successful; in particular, it was not possible to reconstruct the clay ball, neither starting from images obtained from the iPad (C1, C2) nor from the iPad with macro lens (C3) nor from the Canon camera equipped with the 18-55 mm lens (C4). In these cases, the alignment failed, not benefitting from masking undesired parts of the images, collimating markers as reliable points or dividing dataset in chunks. For all the other tests, the photogremmetric processing was successful. In Figure 5, one of the models produced is shown (in particular, the Ugarit tablet obtained from images acquired with the 50 mm lens).

6.2 Laser scanner 3D models

The ScanRider 1.2 produced scaled 3D models in the .stl format. Some details on the geometry of the four models produced are displayed in Table 6. Even if the geometry was reconstructed in detail, it is important to recall that the ScanRider 1.2 does not provide the texture, because it does not have its own RGB camera.

Figure 5: Model of the tablet from Ugarit - 50 mm lens (U2)

6.3 Discussion

The 3D models produced with ScanRider 1.2 clearly highlight how this scanner is actually able to reconstruct also the high frequencies with high resolution, which is an aspect of main interest in this study, given that we are particularly concerned with the inscriptions written on the objects.

As to photogrammetry, the whole set of photogrammetric tests provided several practical suggestions to follow on-site and a series of elements useful to discern the best sensors to use with

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	iPad	Reverse 18-55 mm lens	100 mm lens	50 mm lens
Object	Time			
Clay ball	×	1 h 34 min 50 s	29 min 55 s	10 min 8 s
Tablet from Ebla	×	×	1 h 57 min 2 s	19 min 59 s
Tablet from Damascus	12 min 7 s	×	59 min 35 s	34 min 18 s
Tablet from Ugarit	6 min 17 s	×	×	18 min 4 s

Table 5: Processing time on Agisoft

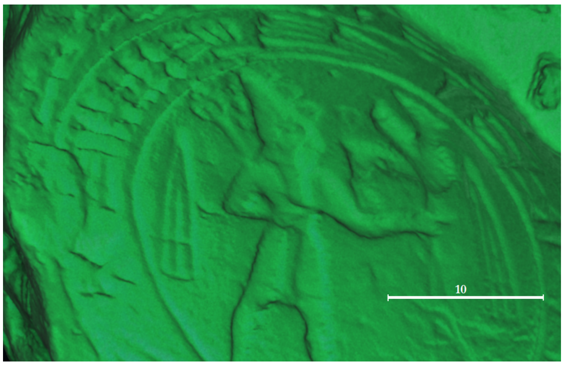

Figure 6: Small detail of the laser scanner 3D model of the tablet from Damascus (scale in millimeters)

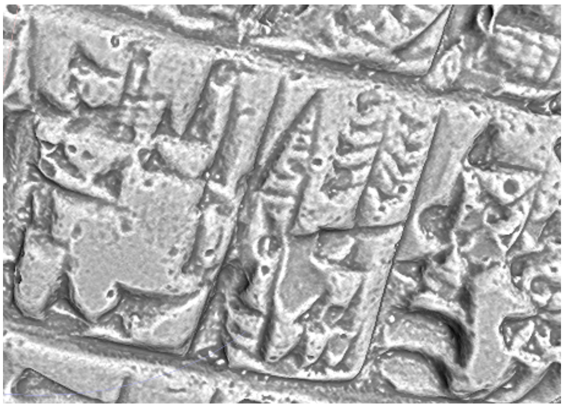

Figure 7: Small detail of the laser scanner 3D model of the tablet from Ebla

respect to the desired goals. First of all, as expected, the necessity of ensuring a uniform lighting emerged; this necessity was partially met by means of a ring flash and a diffuser photo box provided with LED lights. The ring flash, in particular, ensured very uniform lighting, even though this made the clay ball inscriptions hardly distinguishable, in terms of texture, from the object surface in the final 3D model. The tests also showed that a logical and well-planned capturing scenario is preferable to a random one (i.e. the expected result is less uncertain and the image acquisition process is faster), as might be expected given the high geometric complexity of these objects. Another important aspect that emerged is the necessity of a non-invasive and opaque support, preferably covered with targets (such as pieces of graph paper) to allow marker detection for model scaling.

Object	Number of points	Number of faces	Scanning volume
Clay ball	1687154	3374306	V1
Tablet from Damascus	3240532	6481060	V2
Tablet from Ebla	6767990	13536102	V1
Tablet from Ugarit	3016404	6032804	V2

Table 6: Characteristics of 3D model geometry reconstructed with the ScanRider 1.2 scanner for the four replicas

Photogrammetric model	Mean (mm)	Std. Dev. (mm)
Tablet from Damascus - iPad	1.54	0.43
Tablet from Damascus - 100 mm lens	0.08	0.08
Tablet from Ebla - 100 mm lens	0.12	0.16
Clay ball - 50 mm lens	0.00	0.09
Tablet from Damascus - 50 mm lens	0.06	0.07
Tablet from Ebla - 50 mm lens	-0.28	0.13
Tablet from Ugarit - 50 mm lens	0.11	0.09

Table 7: Accuracy and precision of scaled photogrammetric models

Some difficulties occurred during the acquisitions (such as the necessity to capture details on the tablet edges, which is a critical aspect of quasi-two-dimensional object 3D reconstruction) suggested to rely on macro lenses: the tests carried out showed that macro lenses attached to the camera are effectively useful to achieve good results in terms of accuracy and texture restitution, whereas they introduce some problems in the photogrammetric process when connected to the iPad; in addition to this, they have a negative impact on the acquisition time. The use of macro lenses required also to face the problem of the small DoF which is associated to this kind of lenses; in order to avoid this problem without losing their main benefit (i.e. their high spatial resolution, which is fundamental to properly reconstruct the tablet inscriptions), the images - organized in adequate stacks - underwent the focus stacking methodology. Focus stacking was also useful to integrate in the resulting images some details used for marker detection (thus for model scaling).

Nevertheless, if the objects have to be represented in the sharpest way possible, the background ought to be preferably blurry and clearly distinguishable from the object to be reconstructed, in order to help automatic masking of the images. Background was sometimes included in the depth of field: in this cases, it had to be changed together with the object side to be captured.

The comparison among different configurations of cameras and lenses hinged on three elements: geometric reconstruction accuracy, needed time to produce a single model and lens cost. The first element was evaluated by comparing the photogrammetric scaled models to the laser scanning ones, considered as reliable references on the basis of the device nominal accuracy (Table 3) and having observed that also the smallest details were reconstructed (see Figure 6 and Figure 7 for an example). This comparison was realized by importing the models on CloudCompare, by registering them (first manually and then automatically by means of the ICP algorithm) and finally by computing the distances between the point clouds of the photogrammetric models and the mesh of the laser scanning ones, following the procedure described in (Ravanelli et al., 2018). Discrete distance function calculation was then summarized with mean and standard deviation values. In Table 7, the computed values of mean distance and standard deviation are shown for all the photogrammetric models which were provided with scale (negative mean distances correspond to photogrammetric models smaller than their references).

The first thing to note is that the iPad model is much less accurate than the others, with an absolute mean distance that is more than 5 times higher than any other model and a standard deviation 2.5 to 6 times higher.

If we compare the accuracy of the 100 mm and 50 mm lens by considering the tablets from Ebla and from Damascus, we observe very similar results: the tablet from Damascus was even better reconstructed with the 50 mm lens rather than the 100 mm one, whereas the model of the tablet from Ebla obtained with the 100 mm lens was slightly better (probably because it is smaller and more detailed).

Finally, the Canon camera allowed to achieve a precision (or standard deviation), on average, of 0.1 mm (which does not reach the laser scanning nominal precision and represents the noise of the model itself); the absolute mean distance was approximately of the same order of magnitude.

In terms of time efficiency and handiness in operating the sensor configurations, it is worth recalling that the reverse lens system and the 100 mm lens one were quite complex and thus time-consuming; in particular, the latter, which is arguably the best in terms of texture restitution and geometric accuracy, could be used in cases of particular interest only. In addition to this, the processing time measures shown in Table 5 indicate that the reverse lens and 100 mm one are more time-consuming than any other systems, due to the high spatial resolution of the images they allow to acquire.

Finally, if we consider the commercial price of the lenses (excluding the iPad camera, which is embedded in that device), the 18-55 mm and 50 mm lenses have quite similar prices (respectively €80 and €50), while the 100 mm one is much more expensive ($\sim$ €850).

6.4 Integration between laser scanning and photogrammetry

From the results presented so far, it is possible to state that the laser scanner used provides very accurate scaled 3D models in less time than photogrammetry, but these models are not texturized. On the other hand, each model produced with photogrammetry has its own texture, but the level of accuracy and precision is lower than laser scanning. Furthermore, the photogrammetric models produced with the 50 mm lens present a mesh resolution that is not sufficiently high to describe small details such those of Ebla tablet (see Figure 8).

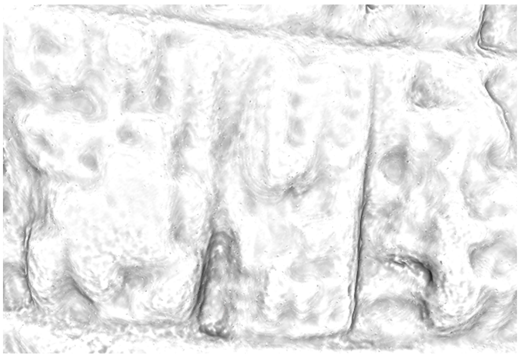

Figure 8: Low mesh resolution of the model of the tablet from Ebla obtained with the 50 mm lens (same detail as Figure 7)

However, by means of Maya commercial software (AUTODESK, 2019a) - available for free to academic users -, it was possible to transfer texture from a photogrammetric model to the corresponding laser scanning one, thus obtaining a very accurate scaled model with texture. This operation was realized by means of a Maya functionality called *UV mapping* (AUTODESK, 2019b): UV mapping defines a relationship between the position of each triangle of a mesh expressed in a 3D reference system and its position in a 2D system with coordinates (U, V). This projection allows to assign to each triangle its corresponding texture (see a portion of an UV map in Figure 9). The idea was then to transfer

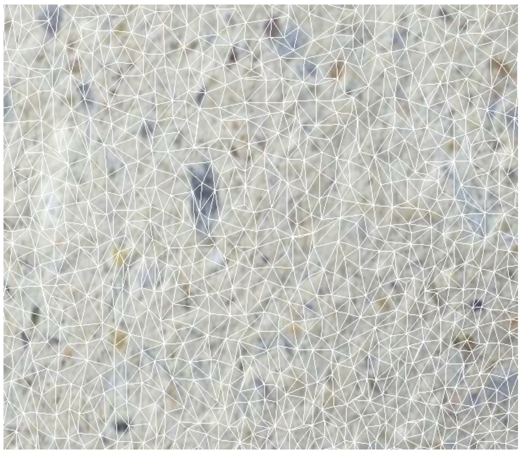

Figure 9: Detail of an UV map

both the UV map defined for a photogrammetric model (automatically created by Agisoft Photoscan) and its texture (organized according to that UV map) to the laser scanning model of the same object. The essential prerequisite was the perfect overlap or alignment between photogrammetric and laser scanning models, which was achieved through CloudCompare (the registration was possible also between non-scaled models and laser scanning ones, because CloudCompare includes a scale adjustment in the ICP automatic process).

This solution was applied to each laser scanning model, while the following photogrammetric models were involved:

- all the 3D models produced with the 50 mm lens;
- the 3D models of the tablets from Ebla and from Damascus generated with the 100 mm lens;
- the clay ball 3D model produced with the reverse 18-55 mm lens;
- the 3D models of the tablets from Damascus and Ugarit produced with the iPad.

The results obtained through this strategy show an excellent overlap between texture and mesh, with the only exception of the 50 mm lens clay ball model, where a small artifact was generated (INSCRIBE, 2018b),(INSCRIBE, 2018c).

7. CONCLUSIONS

In this work, two 3D modeling techniques, photogrammetry and laser scanning, were tested in order to find the optimal sensors and settings functional to acquiring the complete 3D models of inscribed archaeological objects, paying particular attention to the geometric accuracy and operative feasibility in terms of required sensors and necessary time.

With regards to photogrammetry, different cameras and lenses were used and a robust acquisition setup, able to guarantee a correct and automatic alignment of images during the photogrammetric process, was identified. The focus stacking technique was also investigated. The Canon EOS 1200D camera equipped with prime lenses and iPad camera showed respectively the best and the worst accuracy. From an overall geometric point of view, the 50 mm and 100 mm lenses achieved very similar results, but the reconstruction of the smallest details with the 50 mm lens was not perfect. On the other hand, the acquisition time for the 50 mm lens was considerably lower than 100 mm.

As for the laser scanning, the ScanRider 1.2 model was used. The 3D models produced clearly highlight how this scanner is actually able to reconstruct also the highest frequencies of interest with high resolution. However, the models are not provided with texture.

For these reasons, a robust procedure which ensures accurate 3D models with good texture restitution has been defined. It is based on the integration between laser scanning (which provides nominal accuracy and precision of few hundredths of millimeter) and photogrammetry (which provides texture, whose quality depends on the sensor and related equipment involved and on lighting conditions, and which also achieves high accuracy and precision – at most of few tenths of a millimeter). The integration between these two techniques, made possible by UV mapping through software like Maya, produced very accurate texturized 3D models (which represent also the high frequencies).

The same procedure is replicable also on-site, because 20/30 minutes are necessary to acquire a model via laser scanning and at most 40/50 minutes to acquire images (the image processing time is not considered here), if we use a 50 mm lens (which provides models comparable to those obtained by means of a 100 mm lens - in less time - and is much cheaper): this aspect makes it extremely effective also for the 3D reconstruction of a copious set of complex inscribed material.

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