Photogrammetry and Macro Photography. The Experience of the MUSINT II Project in the 3D Digitization of Small Archaeological Artifacts

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The MUSINT II project was created to publicize and promote Minoan glyptic, a little-known archaeological heritage. Its contents were designed to involve both specialists and the general public (adults and children). The project focuses on the 3D digitalization of seventeen very small (ca. 15 mm diameter) seals, stored in the archives of the National Archaeological Museum of Florence. The digitalization of these artifacts required both a high-quality resolution technique capable of capturing their morphology and decorative motifs and also that the resulting 3D models were appealing to the target audience. For this reason, an approach based on Structure from Motion (SfM) photogrammetry was chosen. This technology makes it possible to obtain three-dimensional reproductions from photographs made by non-dedicated devices, but the tiny-object survey required specific instruments and skills in order to be scanned in such a way as to acquire a high quality and shadow-free texture. The macro photography technique was applied together with a specific workflow to obtain high quality photogrammetric models and to save time in acquiring and processing images. With this methodology, 3D models of high metric precision mesh and maximum color fidelity textures were obtained in the Agisoft Photoscan software. This process delivers results with high level detail for low costs and minimal acquisition and processing time (ca. four hours).

Key words:
photogrammetry, macrophotography, macrography, glyptic, interactive museum, workflow.

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1. INTRODUCTION

MUSINT II is a virtual interactive museum related to a single typology of Aegean objects: the whole cache of the sealed administrative documents discovered in the early 1900s during the Italian Archaeological Mission in Haghia Triada, Crete. The presented artifacts are part of the collections of two Italian museums, the National Archaeological Museum in Florence and the Pigorini Museum in Rome. All objects belong to the Neo-Palatial period in Crete.

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The objective of MUSINT II is to overcome the difficulty in accessing these sealed documents; they are in two different museums and are not shown in the permanent exhibition galleries of either. This interactive project was therefore undertaken with the idea of gathering together all these materials into a single virtual and interactive museum. The goal was to meet the general need for a better use of archaeological heritage.

The main targets of MUSINT II are visitors interested in scientific research. They can have simultaneous access both to a 3D representation of the single objects and a database of the whole collection. The interactive museum is designed to meet the highest scientific level; every section presents a virtual landscape, which can be continuously updated with the most recent technological improvements, and with the achievements of archaeological sector as well (Jasink 2016).

The museum also has the goal of attracting a more general public, thanks to the appeal of 3D representations and the help of other resources (photo galleries, renderings, historical data, and so on). An educational section, indeed, is dedicated to young visitors: the aim is to involve them with an active participation in the rediscovery of ancient Minoan civilization.

2. TECHNICAL GOALS

Seventeen Minoan seals are stored in the archives of the National Archaeological Museum in Florence, among the various administrative documents. They range from the Minoan Pre-Palatial to the late Mycenaean period. This Florentine collection comes from acquisitions made between 1906 and 1910 on Crete and in the Greek antiquarian market by the Director of the museum, Luigi Adriano Milani. The exception is one seal (inventory No. 85080) from Phaistos, which was donated by the government of Crete to the museum in 1911.

These seals are very small in dimensions and carved from different materials, mainly semi-precious hard stones like rock crystal and carnelian. Engraved motifs, very detailed, primarily depict animals but also include human figures. Accordingly, the digitalization of these artifacts required a high-resolution technique capable of capturing their morphology and decorative motifs and, at the same time, appealing to a broader audience.

These artifacts are not visible to the public, and it is very difficult to get permission to view and study them. Furthermore, the museum storerooms are very cramped environments, where space for personal work and technical equipment is extremely limited.

For all these reasons, the required 3D acquisition methodology had to be fast, inexpensive, highly precise in shape measuring and accurate in texture acquisition. The Structure from Motion (SfM) technique is the ideally suited to achieve these goals.

3. ISSUES AND SOLUTIONS

The project focuses on the 3D digitalization of seventeen Minoan seals. The main characteristic of these objects is their small size (≈15 mm diameter). To photograph such tiny seals, it is necessary to use the techniques of macrophotography. Working with macrophotography and photogrammetry together, it is necessary to face some issues of both the techniques, as summarized in Table I, which pairs the issues with the adopted technical solutions.

Table I. Solutions adopted to solve the technical problems of digitization.

Issues	Solutions
15 mm diameter objects	Macrophotography. Nikon D800 with Nikon AF-S 105mm f/2.8 G ED VR Micro. 7360pix
Depth of field	≈4mm at diaphragm f/22.
Dark surfaces	Digital developing of DNG files with two set of pictures at different exposition value: overexposed for camera matching and normal for texture generation.
Maximum color fidelity (accurate colorimetric texture without shadows)	Chromatic reference target + profiled camera + high Color Rendering Index (CRI) light sources.
High metric precision mesh	CAD metric reference grid, not using natural points for referencing.
Speed and low cost	Minimal acquisition and processing time achieved with a standardized workflow (4 hours acquisition and editing time for a single seal).

3.1 Objects dimension and depth of field

To photograph the objects, a macro lens with 1:1 magnification rate (a fixed 105 mm focal length) was chosen and the camera was set ≈24 cm far from the object. With this configuration, an 8 cm-base surface was framed, enough to keep the seal inn sharpest focus in the center and to frame at least three markers of the reference grid that surrounded the object.

This configuration presented another very common problem in macrophotography: depth of field (DoF). DoF is the distance between the nearest and farthest objects in a scene that appears acceptably sharp in an image. It varies depending on focal length, diaphragm aperture and focusing distance according to the formula [Ray 2002]:

$$DoF \approx \frac{2NcF^2d^2}{F^4 - N^2c^2d^2}$$

where N is diaphragm, F is focal length, c is circle of confusion and d is distance.

To frame tiny objects in 1:1 scale, it is necessary to employ lenses with very high focal length value (F). This causes the main technical problem of macrophotography: the higher the focal length, the smaller the depth of field. Consequently, images will have a very shallow area in focus. As a general rule, during the reconstruction process, blurred images should be avoided: they can cause difficulties in camera matching or dense point cloud generation. What is more important, however, they will generate artifacts in the final texture; parts of the object will be covered with unfocused parts of the pictures.

To solve this issue in the easiest way, it was decided to close the diaphragm at f/22 to have a calculated depth of field of approximately 4 mm. For this project, diaphragm f/22 was considered a good compromise between depth of field and image sharpness. F/22, however, is a value too far from the optical optimum (f/11) [Williams 1989] to have the sharpest image. To completely solve the depth of field problem, the artifacts should, ideally, be scanned with the focus-stacking methodology [Brecko 2014]; but since this is slower and more costly, it was far beyond the scope of the project.

3.2 Dark surfaces

Some seals are carved on very dark stone. To shoot in a digital negative format, it was important to confront these dark objects. Digital post-processing of negative format permits us to force the exposure value and to create two different chunks of images: one for point cloud creation and one for texture generation. The chunk employed for texture generation was shot at the right exposure value in accordance with the chromatic reference target used for calibration. The same negatives were then post-produced at +2 exposure stops. The overexposed pictures were then used for image matching and dense cloud generation, solving the problem of the too dark surfaces. This process is possible only with digital negative pictures and not with in-camera pre-produced images (JPEG format).

The reason for this limitation is in the lower bit depth and, consequently, the smaller dynamic range of JPEG file format. Digital cameras record each color channel with more precision than the 8-bits (2^8 = 256 levels) per channel used for JPEG images. The RAW images for this project were acquired with 14-bits of precision (2^{14} = 16.384 levels) per color channel, providing several times more information than an in-camera JPEG. Furthermore, higher bit depth decreases the susceptibility to posterization[1] and increases the flexibility when choosing a color space, as explained in section 3.3. The RAW file format, moreover, usually provides considerably more dynamic range than a JPEG file, depending on how the camera creates its JPEG. Dynamic range refers to the range of light to dark that can be captured by a camera before becoming completely white or black, respectively. Since the raw color data has not been converted into logarithmic values using curves, the exposure of a RAW file can be adjusted slightly after the photo has been taken. Exposure compensation of a RAW file can bring out lost shadows or highlight detail, as not possible with a JPEG file.

3.3 Texture color fidelity

Working in RAW permitted us, moreover, to have total control of the color process. After the photographic set was prepared, an X-rite ColorChecker Passport was placed in the middle of the set and illuminated with a high Color Rendering Index light source (halogen) to make the colorimetric calibration of the camera and the setup.

The ColorChecker is a chromatic reference target that can be used in a digital workflow for color management: white balance, exposure control and the camera's colorimetric profiling. This permits users to achieve the best color fidelity possible.

3.4 High metric precision mesh

To control the mesh quality and metric reference of the model, the surface of a turntable was printed with a metric reference grid of markers. The grid was drawn in concentric rings of eight markers in

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[1] Posterization occurs when an image's apparent bit depth has been decreased so much that it has a visual impact. Any process which "stretches" the histogram has the potential to cause posterization.

AutoCAD. To set the UCS position and the drawing unit permits us to know the spatial coordinates of every marker and to import them into the photogrammetric software to scale the object and control the reconstruction error.

3.5 Low cost

To keep the cost for the digitalization process low was important owing to the limited funds available for the project. The easiest way to respect the budget limit was to keep acquisition and process time minimal. For this purpose, a standardized workflow was created and applied in the digitalization process of every marker.

4. WORKFLOW

The workflow is divided into eight steps, as shown in Fig. 1:

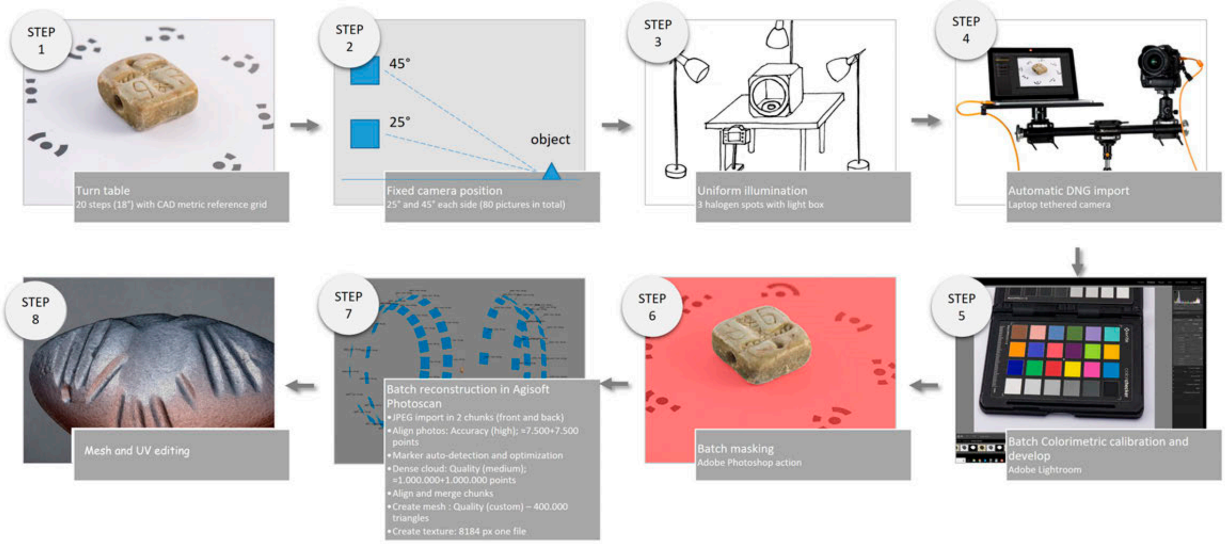

Figure 1. Detailed workflow steps.

4.1 Acquisition setup

1) A seal is placed in the middle of a turntable, surrounded by markers.
2) The camera is positioned in front of the subject. Its position is fixed, varying only the shooting angle (2 different angles, 25 and 45 degrees, for each side of the object).
3) To guarantee a uniform illumination and avoid casting shadows, which could ruin the texture and limit the model use, the turntable was placed inside a light box to diffuse the three surrounding halogen lights.
4) The camera was tethered to a laptop to speed the file transfer.

5) The pictures were imported directly in Adobe Lightroom for colorimetric calibration and pre-processing.
6) An Action was created in Adobe Photoshop for batch masking every picture.
7) 3D reconstruction was undertaken using Agisoft Photoscan.
8) The mesh and UV map were edited.

The setup with the fixed camera position can generate issues in picture alignment because of the change of the shadow's position on the object. The problem can be partially solved with a very uniform illumination, casting no net shadows or specular reflections. Despite this problem, our approach proved very suitable because it permitted us to keep the frame and focus point fixed, considerably reducing the acquisition time.

The camera was a full-spectrum[2] Nikon D800 with a full frame sensor of 36.3 MP, equipped with an AF-S VR MICRO-NIKKOR 105 mm F/2.8 G IF-ED. This specific objective has very low distortion (0.2%) and supports a high-resolution camera.[3] Moreover, it is able to frame at a 1:1 magnification rate without having to approach too close to the object (≈24 cm), which could create operational problems like unwanted shadows or reflections.

4.2 Lighting

Uniform illumination was ensured by placing the seal inside a lightbox, a translucent box that diffuses the transmitted light. The object was lit up with three halogen lights. This light source was preferred for its very high Color Rendering Index value (Ra≈100). It permits the best color distinction, reducing illuminant metameric failure[4] [Edwards 1989].

This scheme of illumination removed any net shadow on the seals, facilitating the matching of homologous points from the software and building a shadow-free texture.

4.3 Metrical and chromatic references

Within the lightbox, the seals were placed on a turntable that allowed the object to rotate on its central axis. The plate surface was printed with a reference grid of targets, as explained above. The marker system is automatically recognized by the photogrammetric software.

The very first shot of the acquisition process was for acquiring the chromatic reference, the X-rite ColorChecker Passport.

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[2] The camera had been modified by removing the IR low-pass filter (hot-mirror) and the anti-aliasing filter to enhance the image sharpening. A new low-pass filter was mounted on the lens during the shooting to acquire only visible light.

[3] The data (distortion and Perceptual Megapixel) are found in dxomark.com using the model D800E equivalent in sharpening at D800 without hot mirror and anti-aliasing filter: https://www.dxomark.com/Lenses/Nikon/AF-S-Nikkor-VR-105mm-f-2.8G-ED-mounted-on-Nikon-D800E---Measurements__814

[4] In colorimetry, metamerism is a perceived matching of the colors that, based on differences in spectral power distribution, do not actually match. The term illuminant metameric failure or illuminant metamerism is used to describe situations where two material samples match when viewed under one light source but not another.

4.4 Method of shooting

Every seal was photographed by considering only one half at a time. For each half were performed a minimum of forty (20+20) photographs by turning the base 18° between shots and varying the camera angle (25° and 45°), to ensure the observation of the object in all its parts.

Each seal was framed in the center of the view, to exploit the maximum lens sharpness and reduce the optical aberration. The magnification was appropriate to have from three to eight markers visible in every shot.

The photos were made at aperture f/22, 2.5'' shutter speed and ISO 100.

All photographs were recorded in the native Nikon NEF digital negative.

The transfer data was automatized by tethering the camera to a laptop. The transfer was managed by the Tethered Capture tool of Adobe Lightroom.

4.5 Pre-Processing

Every acquired picture was automatically imported in Adobe Lightroom 6.

All photographs were recorded in the native Nikon NEF digital negative and converted in Adobe DNG, the open source format developed by Adobe for storage[5] [Bennett 2010].

The aim of the pre-processing phase of digital negative files was to facilitate searching for homologous points by the photogrammetric software [Ballabeni 2015] and to have radiometrically-calibrated images ensuring the consistency of surface colors along all the images.

With respect to color characterization, the color targets based technique [Hong 2001] was adopted, using a set of differently colored samples measured with a spectrophotometer. The target XRite ColorChecker [McCamy 1976] was employed during the image acquisitions, considering the measurements of each patch [Pascale 2006] and used as a reference for exposure equalization and color balance. The use of the color target is necessary in order to have an accurate color acquisition, because, as in Hong, the RGB signals generated by a digital camera are *device-dependent*.[6] Furthermore, they are not colorimetric (i.e., the output RGB signals do not directly correspond to the *device-independent* tristimulus values based on the CIE standard colorimetric observer). To obtain a *device-independent* calibration, the XRite ColorChecker Camera Calibration software was used. It matches the photographed physical reference chart with a reference chart color space with ideal data values for the chart and creates a means for converting the device color space to the reference chart color space. The ColorMatrix and HueSat, a Hue Saturation Light (HSL) variation sheet, are integrated in a dcp color profile that can be used at the beginning of the pre-processing phase.

DNG files were adjusted, as shown in Table 3, and saved in JPEG (quality 12, sRGB color profile).

Table 3. Pre-processing in Adobe Lightroom 6.

[5] https://helpx.adobe.com/it/photoshop/digital-negative.html
[6] Different digital cameras produce different RGB responses for the same scene.

Options	Details
Color balance – color temperature	Personal - set with the 18% gray reference surface on the ColorChecker
Color balance - camera calibration	Process: 2012 Profile: generated with ColorChecker Camera Calibration software
Exposure equalization	Set with the 18% gray reference surface on the ColorChecker
Clarity	+30
Sharpening	Amount: 75; Radius: 1,0px; Details: 50
Camera calibration	Process: 2012 Profile: generated with ColorChecker Camera Calibration software

4.6 Masking

The workflow for 3D reconstruction of very small objects here presented uses a fixed setup: the camera is on a tripod and a series of photographs is taken of the specimen on a turntable that is rotated across a small angle between shots. It results in the object and the turntable plane changing position and the background presenting the same features in every picture. The non-turning background must be masked, so that no points are detected on it [Mallison 2014].

Masking can be performed in two different ways: directly in Agisoft Photoscan or in an external graphics program, where the area can be selected manually by painting in or lassoing, or automatically using a magic wand tool or quick selection tool. The second option presents the possibility of speeding up the process, creating a script for batch processing.

1) The developed JPEGs were imported in Adobe Photoshop
2) The background was selected with Quick Selection tool with no Refine Selection Edges option
3) Layer > New Fill Layer > Solid Color > R 0 G 0 B 0 (with Selection Mask on)
4) Layer > New Fill Layer > Solid Color > R 255 G 255 B 255
5) Switch the two Fill Layers order
6) Save as JPEG
7) Close

The whole process from step 2 to 7 was saved as an Action for batch processing.

4.7 Modeling

The model was developed in two chunks, one for each side of the seal, in Agisoft Photoscan 1.2.1. The software was chosen for its reliability [Marčiš 2013] and computational speed [Remondino 2014]. Moreover, its chunk-based interface is suited to the digitization protocol adopted for this project, which uses the union of two different chunks for every seal [Mallison 2014].

The realization of the model followed the steps shown in Table 4.

Table 4. 3D Reconstruction process in Agisoft Photoscan 1.2.1.

#	Phase	Description
1	Align photos	Accuracy (high); Constrain features by mask – on average ≈7,500+7,500 points
2	Reference	Auto detect markers; import coordinates
3	Point cleaning and alignment optimization	Gradual selection and cleaning of the points
4	Dense cloud	Quality (medium) – on average ≈1,000,000+1,000,000 points
5	Align chunks	Method (marker based) identified three points common to the two sides
6	Merge chunks	-
7	Create mesh	Quality (custom) – 400,000 triangles
8	Create texture	8184 px in single file

According to the values specified by the software, the average error in the camera matching phase is 0.176 mm and 0.297 pixels on a 26mm diagonal bounding box (Table 5).

Table 5. Metric error and pixel error for every seal. The objects are divided in two chunks, one for each side.

Seal	Error (m)	Error (px)	Seal	Error (m)	Error (px)	Seal	Error (m)	Error (px)
82528	0,000084	0,757	82691	0,000065	0,819	84587	0,000059	0,056
	0,000042	0,145		0,000062	0,348		0,000135	0,172
82529	0,000044	0,028	82692	0,000144	0,879	84593	0,000661	0,115
	0,000019	0,019		0,000139	1,025		0,000892	0,512
82530	0,000028	0,363	82820	0,000062	0,003	84707	0,000095	0,21
	0,000061	0,056		0,000082	0,007		0,000103	0,574
82590	0,000141	0,863	82821	0,000581	0,069	84708	0,000141	0,035
	0,000141	0,901		0,001244	0,085		0,000033	0,137
82665	0,000171	0,056	82822	0,000099	0,041	85080	0,000056	0,156
	0,000171	0,056		0,000108	0,093		0,000063	0,413
82690	0,000059	0,111	82823	0,000065	0,285			
	0,000064	0,059		0,000057	0,426			

The models obtained were then exported to OBJ format for sharing.

5. TIME SCHEDULE.

The whole process required approximately four hours (Table 6), excluding set up time (it was done once for all the acquisitions) and editing. The acquisition and developing required thirty minutes in total for every seal, plus 15 minutes for masking.

The computational work was completed in approximately three and a half hours with an Intel Core i7-6700K Skylake @4.00GHz, 32 GB RAM, NVidia GeForce 970 with 4 GB RAM.

Table 6. Digitalization process time schedule.

Step	Time (average one seal)
Set-up	- (2h for all the data set)
Acquisition	20'
Pre-processing	10'
Masking	15'
Reconstruction	3h15'
Editing	(if necessary)

Figure 2. 3D models of three seals with (1) texture, (2) mesh, (3) wireframe after decimation.

6. CONCLUSIONS

To create a SfM model using macrophotography is challenging for its technical problems, especially if it must achieve the three stated goals of this project: to be fast, highly precise in shape measuring, and accurate in texture acquisition.

The first goal was achieved thanks to an optimized workflow that used many batch processes and time-saving measures. With respect to the second goal, a very highly precise mesh was obtained with an average error of 0.176 mm and 0.297 pixels. The third goal was achieved thanks to paying careful attention to color fidelity and obtaining shadow-free textures.

Despite the good results of the project (Fig. 2), the digitalization process used in MUSINT II has highlighted a critical point: the depth of field. A solution could be in the focus stacking method, a computational photographic technique for digitally enhancing the depth of field, but very demanding in acquisition and computation time. The analysis of this method is currently part of a separate ongoing project.

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