3Dino: Configuration for a Micro-Photogrammetric Survey

Applying Dino-Lite microscope for the digitalization of a cuneiform tablet

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Close-range photogrammetry, due to the possibilities offered by the technological evolution of acquisition tools and, above all, the relative original challenges posed to surveyors and the theory of measurements, deserve constant critical attention. The new opportunities to detect and represent reality are mostly focused on historical architecture, referring to consequent orders of magnitude and restitution scales. On the other hand, the formalization of relevant practices for very small objects is not frequently addressed. In recent tests carried out using two Dino-Lite handheld digital microscope models, polarized light digital microscopes generally used in medical and industrial fields, we proved the potential of using these imaging systems also for Cultural Heritage documentation, highlighting, however, some issues related to the depth of field and the consequent acquisition geometry. Therefore, this study aims to solve these problems, increasing the performance of microscopic photogrammetry by optimizing the acquisition procedures with the design of custom accessories for micro-photogrammetry (e.g. a calibrated plate). These developments will be carried out as part of a technology transfer agreement with the Dino-Lite company pointed to codify a protocol for high accuracy photogrammetric documentation of small artefacts.

Keywords: *Digital Heritage, Small artefacts, Detailed 3D shape, Handheld microscope*

INTRODUCTION

The configuration of new survey approaches for Cultural Heritage's digitization in terms of conservation, management, and promotion is gradually asserting itself within the so-called "fourth industrial revolution". The possibilities offered by Industry 4.0 thicken the network of relationships of complementarity and interaction between the different disciplines related to imaging and three-dimensional processing, including manufacturing industry, medical sciences, entertainment and, of course, Cultural Heritage (Pieraccini et al. 2001). In particular archaeological disciplines are greatly interested in using emerging and available digital techniques and technologies provided by Geomatics aiming at rigorous objects description (Bitelli et al. 2007) and preservation of human heritage, at least in digital format, by developing the concept of “preventive and planned conservation”, for the restoration field, here declined in order to establish a “preventive digital memory” (Carlucci 2016). Furthermore, given the recent inaccessibility conditions, rethinking representation and visualization phases of the assets constitute a possibility for remote sharing, as well as the establishment of a vast system of information storage, editable and implementable at any time (Apollonio et al. 2021), as well as the representation of real-world heritage for interaction and virtual experience (Djuric et al. 2019).

Usual procedures for documenting heritage objects are mainly addressed to orders of magnitude and architectural restitution scales, but still little oriented towards the coding and formalization of relevant practices for very small objects. In fact, interfacing with small finds represents a not easy challenge determining a change in the representation scale and a rethinking of the acquisition operating systems, not always in comfortable contexts (Plisson and Zotkina 2015). In particular, applications for Cultural Heritage have stricter requirements on morphological details, whose correct reproduction necessarily refers to other factors such as object’s size and shape and surface’s reflective properties - whether it is opaque, glossy or translucent (De Paolis et al. 2020). Several solutions for micrometric applications (Hansen et al. 2006), including range-based ones (Tolksdorf et al. 2017), are increasingly succeeding in the field of Cultural Heritage study. However, not infrequently, certain optical or mechanical limitations, the need for specialized operators and the considerable costs direct the interest towards precision photogrammetry, which offers the possibility of obtaining the three-dimensional (3D) coordinates of an object from two-dimensional (2D) digital images in a rapid, accurate, reliable, flexible and economical way (Yilmaz et al. 2008). In detail, the possibility of using photographs taken by a digital microscope as a dataset for photogrammetric processing revealed a not negligible potential for small objects modeling, reaching about 0,1 mm accuracy (Esmaeili and Ebadi 2017). A digital microscope is similar to a traditional optical microscope except that it is equipped with a CCD camera so that it can output a digital color image to a monitor, and among the main types of a microscope are the most flexible and the least expensive (Atsushi et al. 2011). Digital portable microscopes, born for inspection, documentation, and digital metrology analysis - already popular in the manufacturing and quality control industry, as well as used in the medical field - are easy to handle and versatile capturing systems. On the other hand, the images they provide do not have both: very high resolution (usually not exceeding 5 MP) and wide dynamic range. In addition to these problems, the narrow Field Of View (FOV) and shallow Depth Of Field (DOF), which could compromise close-range photogrammetry, should be mentioned. These limitations could, in fact, affect point matching, the number of conjugate points computed, and the resolution of the 3D model (Kontogianni et al. 2017), also determining an increase in acquisition times because it makes necessary to move the microscope often to cover the object. In this case, the acquisition automation would make the entire process more advantageous (Mitchell and Kniest 1999).

Case study

One of the current challenges is to configure a high-performance micro-photogrammetric system using the now widely available on the market digital portable microscopes. The main aim is to test their validity on micro-scale survey, overcoming the obvious operational difficulties, especially in the acquisition phase. For this purpose, in this current work, the authors will focus on the systematization of individually available hardware tools to explore microscopic photogrammetry and define a standard procedure for the acquisition of very small objects. Therefore, it is proposed the procedural solutions identified to carry out the digital survey of a 3D printing replica [1] in geopolymer of a tablet with cuneiform writings. The text content concerns the administrative information for fish deliveries (a modern correspondent of a packing slip). Its dimensions are approximately 20 x 22 x 8 mm, and the characteristic wedge-shaped impressions have a depth of 1-3 mm (see Figure 1).

Figure 1
Recto and verso views of the 3D printed copy of the cuneiform tablet

This paper focuses on studying the most suitable 3D measurement instrumentation and method to achieve a digital replica of this tiny, complex, and detailed object. For the survey tests, it was used the 3D printing replica, as challenging as the original, with the intention of preserving the original spirit of multidisciplinary research that aims to use a physical (or digital) replica of the tablets for scientific purposes. To achieve an adequate descriptive quality and evaluate results soundness, the survey was conducted with two different Dino-Lite portable digital microscopes (www.dino-lite.eu). The quality, speed and cost-effectiveness of this first method were then compared with the data obtained from a Nikon full-frame camera combined with macro optics. All photogrammetric results were compared with an active sensor, the SCAN in a BOX structured light 3D scanner, used as a reference.

MATERIALS AND METHODS

3Dino Plate

Digital close-range photogrammetry exploits several photographic captures taken from different viewpoints for accurately measuring objects and build a digital 3D model. Compared to the canonical close-range photogrammetry acquisition, a redesign of the acquisition hardware system at the dimensional scale is required to solve some critical issues strongly amplified at a sub-millimeter level. In detail, the innovative micro-photogrammetric scanning system proposed in this study, called "3Dino System", is based on the combined use of a three-dimensional calibrator and Dino-Lite handheld digital microscopes.

One of the main problems is the need to include in the scene metric references or calibrated objects and, even by solving this difficulty, to be able to produce an adequate calibration pattern according to the magnitude of the object to be measured (Lavecchia et al. 2017). To address these issues, a calibrated plate - designed by the authors and built for the occasion - was used to optimize, align and for scaling procedures (see Figure 2). This calibrator, called "3Dino Plate", consists of a PLA plate obtained with 3D filament printing, characterized by an orthogonal pattern of 99 truncated cone holes, with a countersink angle of 60° and a smaller base diameter of 0,35 mm. The calibrator accuracy, based on the 3D printing settings [2] and the conformity of the actual position of the holes with respect to the project file, has been estimated at 0,1 mm, which can be assumed as an instrumental error value (i.e., markers accuracy).

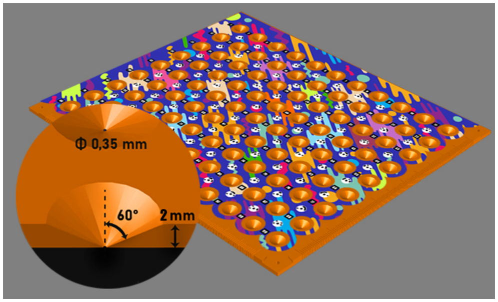


Figure 2
The three-dimensional calibrator "3Dino Plate" and detail of the section of one of the truncated cone holes

The coordinates of each hole, in a local reference system, are therefore known to the operator and can be imported into the photogrammetric project and linked to acquisitions. This allows the use of the perforated pattern as a constraint points (GCP) grid - homogeneously distributed throughout all the area - to optimize cameras alignment. To guarantee sufficiently robust results during the alignment phase, an adhesive geometrically and chromatically non-repetitive pattern, equipped with coded targets, was printed and applied on the calibrator.

The difficulty of manually conducting microscope acquisitions represents a further obstacle. To facilitate and speed up the acquisition phase, a portion of the calibrated plate was set on a plane allowing the object movement. Using the digital microscope housed on a vertical bracket at a fixed angle, a series of images with sufficient overlap can be taken just by sliding the calibrated plate manually once the magnification rate has been chosen (see Figure 3).

The main problem encountered in microscopic optics is the short Depth Of Field (DOF), and it is emphasized when increasing magnification. This allows having in focus only a small portion of the artefact so that only a small portion of the image appears sharp enough to be used for 3D reconstruction (Clini et al. 2016). In fact, the sharpness, joint with density and the resolution of the photoset, will determine the quality of the output point cloud data (Westoby et al. 2012).

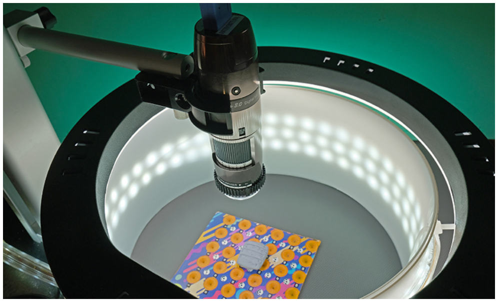


Figure 3
"3Dino Plate" here combined with the Dino-Lite microscope in the "3Dino System"

To overcome the problem of the short DOF, one possibility would obviously be to close the aperture of the optics as much as possible within the limits of the diffraction phenomena (Sapirstein 2018). Since this possibility is not available on portable digital microscopes, where the diaphragm is fixed, it is necessary to use alternative solutions. For this purpose, the object is acquired from various focus planes by moving the microscope on a micrometric vertical rail to focus on different planes without changing the distance between the object and the optical centre.

Dino-Lite digital microscopes

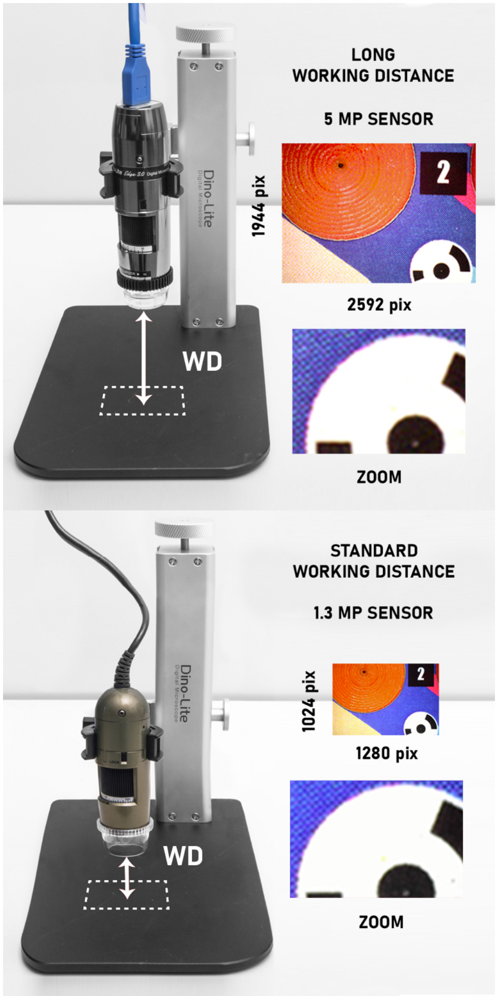
Dino-Lite digital microscopes provide a powerful, portable, and functional solution for detail inspection. The models compared for this first experimentation, *Universal (AM4113ZT)* and *High Speed, (AM73915MZTL)* belong to two different categories, both in terms of technical characteristics and of special features, consequently falling into very different price ranges (see Table 1).

Table 1
Dino-Lite microscopes technical specifications for the models used

Model:	Dino Universal	Dino High Speed
Diffuser available:	Optional	Yes
Polarizer:	Yes, linear	Yes, linear
Magnification:	10-70x, 200x	10-140x
Working Distance:	Standard	Long
Resolution:	1.3 Megapixel (1280x1024)	5 Megapixel (2592x1944)
Maximum Frame rate:	30 fps	45fps (max 20fps for video recording)
Interface:	USB 2.0	USB 3.0
Special features:	No	Auto Magnification Reading Extended Dynamic Range (EDR) Extended Depth Of Field (EDOF) Flexible LED Control (FLC)
Price range:	€200,00 - €350,00	€1000,00 - €1250,00

The element that clearly distinguishes the two microscopes is the Working Distance (WD), i.e. the linear distance between the tip of the microscope nozzle and the subject (see Figure 4). This factor directly affects the Magnification Factor (MF), Field of View (FOV) and Depth Of Field (DOF).

Figure 4
Working Distance reached by the High Speed microscope (top, 75,5 mm) and by the Universal microscope (bottom, 21,7 mm), housed on the stand and operating at the same magnification (30x). Specifically, the acquisition of a relative portion of the calibrator and a detail of the pattern (ZOOM).

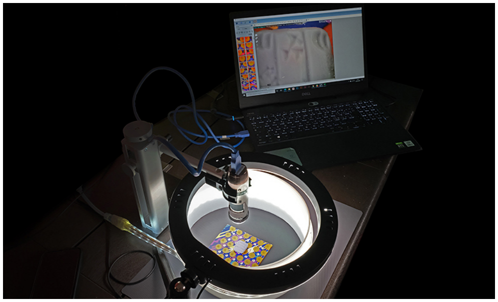


It is trivial to observe that a right compromise must be established between these factors, bearing in mind that the further you are from the subject (high WD), the lower the Magnification, with a wider Field Of View and more Depth Of Field; conversely, the closer you are to the subject (low WD), the greater the Magnification, with a smaller Field Of View and less Depth. Therefore, the WD is an extremely important parameter from a practical point of view and inevitably binds the use of different magnifications in the operational phase.

The lighting conditions, based on the polarized light of the microscopes, have been improved with the adoption of two LED illumination rings, one which is around the object and the other above it. The light does not directly affect the object because of a cylindrical panel consisting of diffusing material, placed between the object and the light source: thus, diffused light conditions neutralize the shadow cones - without variations in the intensity of shadows, lights and colours.

Both *Universal* and *High Speed* models were combined with the 3Dino Plate System, fixing the microscope in the special Dino-Lite RK-10-EX stand and connecting it to a portable workstation (see Figure 5). Hence, the acquisitions were carried out with the same magnifications, 30x, operating with the dedicated *DinoCapture 2.0* procedure (www.dino-lite.eu/index.php/it/software-dino-lite).

Figure 5
"3Dino System" with the special LED ring lighting set-up



Acquisition with Nikon camera

The validation of Dino-Lite digital microscopes results was supported by the photogrammetric survey with a Nikon D810 SRL and the calibrator 3Dino Plate, also suitable for digital cameras.

The best optical systems for small objects are the macro lens and, as well as allowing the close focus in order to maximize the data quality, they also represent, among the types of optics, those optically less affected by distortions.

In our case, an AF-S VR Micro-Nikkor 105 mm f/2.8G IF-ED was used, which allows a minimum focusing distance of 0,314 m. In this case, it was possible to manage the shallow Depth Of Field and the related problem of blur starting from the concept that the Depth Of Field increases with the decrease of the aperture with the consequent reduction of the amount of light passing through and the relative increase in exposure times (Greenleaf Allen 1950). So, an aperture of f/36 was used, shooting at about 35 cm, thus ensuring a DOF equal to about 2 cm. A camera trigger system was used to remotely activate the shutter on the camera and reduce the vibrations, which are not negligible due to the relatively long exposure time (see Figure 6).

Tie points error reduction and optimization

The datasets obtained by Dino-Lite microscopes and by Nikon camera were thus processed in a SfM software, *Agisoft Metashape*, according to the general photogrammetric workflow (see Table 2 and Table 3) and the processing was completed with the same graphic workstation equipped with Intel I9 9900k CPU, RTX2080ti GPU, and 64GB of RAM.

The sparse point cloud, made only by tie points (TPs), is the starting point for the realization of a complete 3D model. However, the removal of low quality TPs is appropriate because their presence affects the results of the next steps, which consist in the recomputation of the orientation parameters, and the creation of the final dense cloud (Barba et al. 2019).

Figure 6
"3Dino Plate" and Nikon setup configuration for the photos acquisition. Take a look at the digital model here: https://skfb.ly/on67U

Model	Dino Universal	Dino High Speed	Nikon D810
Aligned Cameras	501/502	507/591	167/167
Sparse Points	2,4 x10^5	2,0 x10^5	8,0 x10^5
Dense Points	1,0 x10^6	0,8 x10^6	3,1 x10^6
Ground Resolution	9,77 µm/px	4,82 µm/px	5,64 µm/px
RMS	0,324 px	0,797 px	0,829 px
Check Points Error	0,076 mm	0,44 mm	0,089 mm

Table 2
Recto Agisoft Metashape survey data comparison

Model	Dino Universal	Dino High Speed	Nikon D810
Aligned Cameras	501/502	507/591	167/167
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RMS	0,324 px	0,797 px	0,829 px
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Table 3
Verso Agisoft Metashape survey data comparison

The evaluation of image orientation quality within SfM methods can be performed using the Gradual Selection filter tool by *Agisoft Metashape*, which - like most photogrammetric software - allows you to filter the sparse point cloud based on some quality parameters. The parameters considered in this study were: Reconstruction uncertainty, Reprojection error and Projection accuracy.

REFERENCE MODEL EQUIPMENT

The instrument employed - to have a reference model and check the overall geometrical dimensions of the photogrammetric reconstructions - is the SCAN in a BOX (@2015 Open Technologies SRL). The system is equipped with two high-resolution industrial USB cameras and a high definition light projector (ASUS S1). All components are fixed on a thick aluminium rail, but the cameras can be moved in calibrated positions (base) to customize the work field (see Figure 7).

The main steps for the 3D measurements workflow are: i) calibration of the optical setup, ii) range maps acquisition, iii) raw alignment, iv) alignment optimization and v) meshing.

Whenever the scanner is mounted or the camera setting on the support bar changes, the system needs to be configured and calibrated. The coded calibration master has three different patterns based on the working area selected. The optical setup provides for projector and cameras configuration (position, orientation, focus, exposition). The calibration allows calculating the optical parameters of the specific setting.

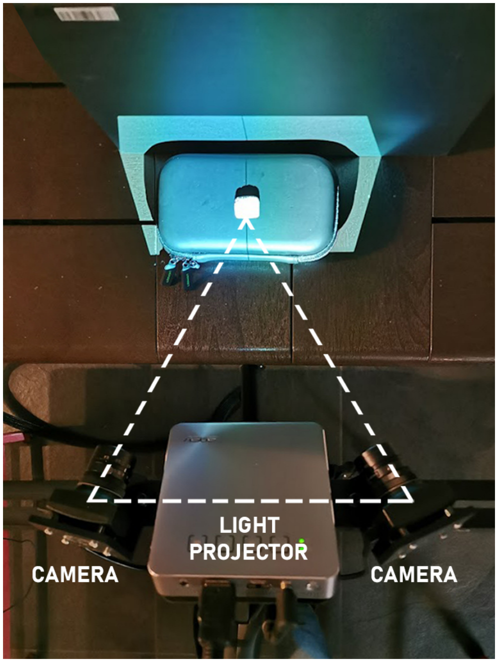


Figure 7
The "SCAN in a BOX" system

According to the object dimension and the resolution required, it is to choose the scanning area more suitable, strictly connected to the working distance and the distance of the cameras on the plate. For our case study, a Field Of View of 100 x 80 mm was set that implies the working distance scanner-object of about 200 mm, the minimum base between the two cameras and the minimum point spacing (resolution) on the surface 0,078 mm.

The digital reconstruction of the object surface and details was performed acquiring: 16 nadiral scans on both sides (8 for the verso and 8 for the recto), 16 tilted (8 for each side) and 8 nadiral to the four edges (totally of 40 range maps). The scanning time for each range map is less or equal to 4 seconds. The raw in progress alignment process was very useful to check real-time scan completeness. This initial registration is then optimized using an Iterative Closest Point (ICP) algorithm. The final mesh model (formed by about 400.000 polygons) have fewer details of the correspondent photogrammetric models but can be used to ensure a reference check of their global measures (see Figure 8).

DATA ANALYSIS

The aim of this analysis is to compare the procedures adopted to digitize of the cuneiform tablet with the various technologies.

The first consideration concerns the difficulty with the current 3Dino configuration and camera setting in acquiring the two sides of the object in a single set of photographs. This problem is related to the acquisition geometry and the calibrator shape. Two sets of images, one for recto and the other for verso side, do not have enough points in common to be merged into a single model. It would have been necessary the acquisition of the very thin edge. In this case, we would have had a depth of field problems that could have compromised the alignment of this possible set of additional images.

A further consideration concerns the management procedures of the images in *Agisoft Metashape* for data and products obtainable with microscopes and camera. More specifically, among the most obvious and limiting digital microscopes problems, there is the absence of Exif data. This information associ-

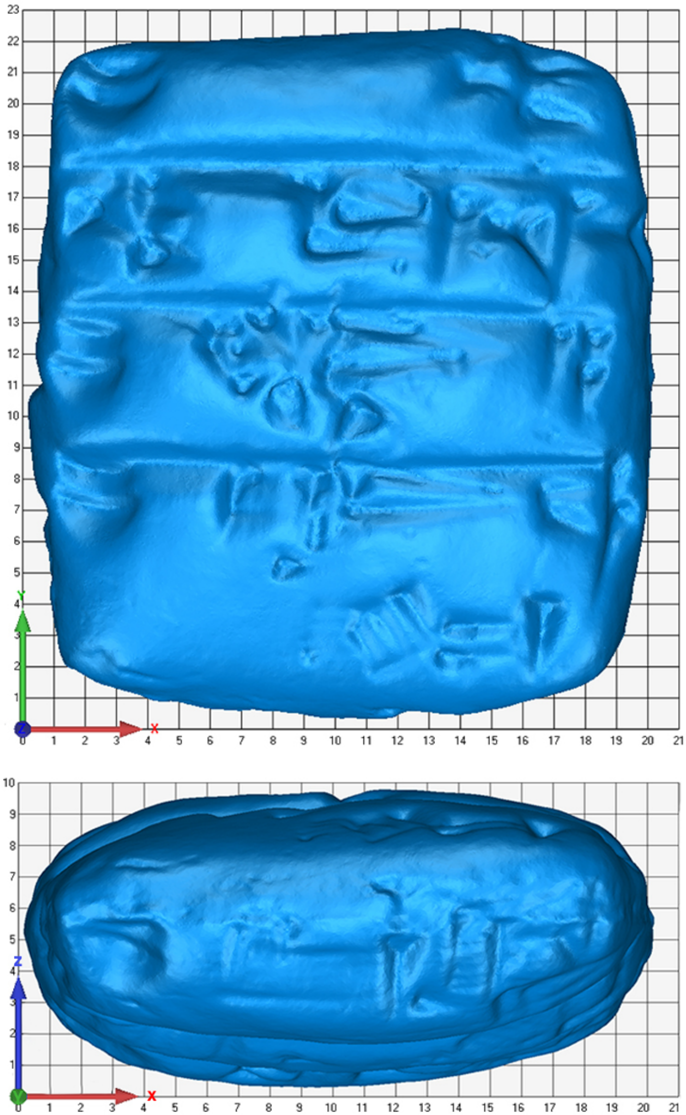
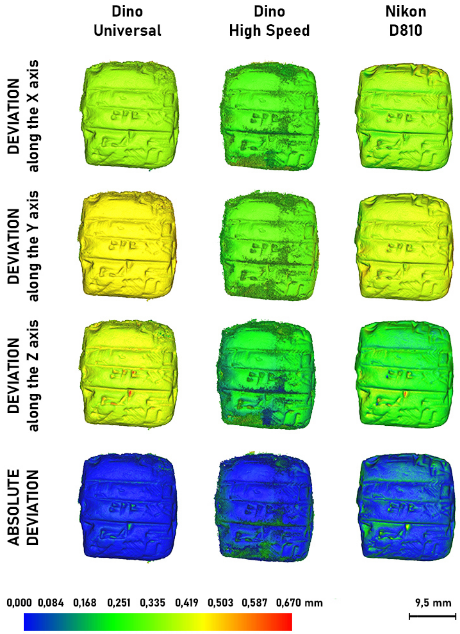


Figure 8
“SCAN in a BOX” polygonal model (1 mm grid background)

Figure 9
Global and relative deviations of micro-photogrammetric dense clouds compared with the "SCAN in a BOX" used as reference model (verso side)



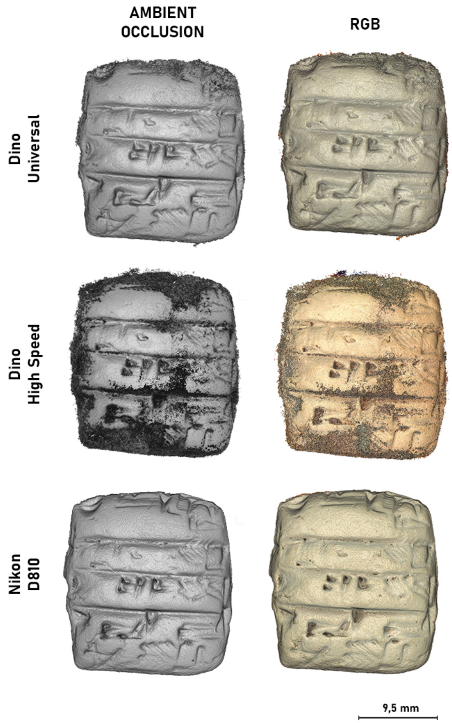
ated with the pixel matrix, as well known, retains data relating to the camera model, sensor size and focal length, and are essential variables, in the absence of laboratory calibration, used by any software to perform adequate calculations for the internal and external camera calibration. Therefore, the uncertainty generated by the absence of Exif data must be considered as a further detrimental parameter for the alignment processes.

To provide a robust comparison [3] for the point clouds, a cloud to cloud registration has been performed using the data coming from the SCAN in a BOX as reference. The registration was carried out in two steps, providing: first, a manual registration using homologous points and then a global registration by automatic alignment algorithms (ICP[4]).

The photogrammetric survey accuracy assessment was carried out using CloudCompare C2C (cloud to cloud) command. This tool searches, for each point being compared, the closer one in the reference entity, thus defining a shift value of the first with respect to the second. Using the cloud generated by the SCAN in a BOX as a reference, the clouds obtained from photogrammetry were compared.

The Figure 9 shows in false colours the deviations among the clouds. Through the calculations performed it is noted that the mean and standard deviations do not exceed the instrumental accuracy of the 3Dino Plate (0,3 mm).

The comparison procedure showed a difference on the Z axis of the model compared with the reference one.



This difference could have been determined by both the registration procedure and the higher resolution obtained from the photogrammetric survey performed with Nikon and Dino *Universal*. The noise, due to alignment problems, of the photogrammetric set acquired with Dino *High Speed* is evident. Absolutely comparable, and perhaps of slightly higher quality than the SCAN in a BOX, are the results coming from Dino *Universal* (see Figure 10 and Figure 11).

A final consideration concerns the parameters: cost, time and quality of output. In this regard, with a cost of a few hundred euros and a quality comparable to that obtained by Nikon and SCAN in a BOX, the Universal microscope is one of the most interesting instruments. The flaw concerns the acquisition time, still long (about 3-4 hours for 500-600 captures) that can be shorten with the design of an automatic capturing system.

CONCLUSIONS AND FUTURE DEVELOPMENTS

The experimental tests conducted with Dino-Lite instrumentation are valid for defining a first approach to the photogrammetric use of portable USB microscopes.

The quality/price ratio of Dino-Lite microscopes, combined with the obtainable high resolution, undoubtedly represent the method strengths. Portability and ease of use are two additional and significant qualities.

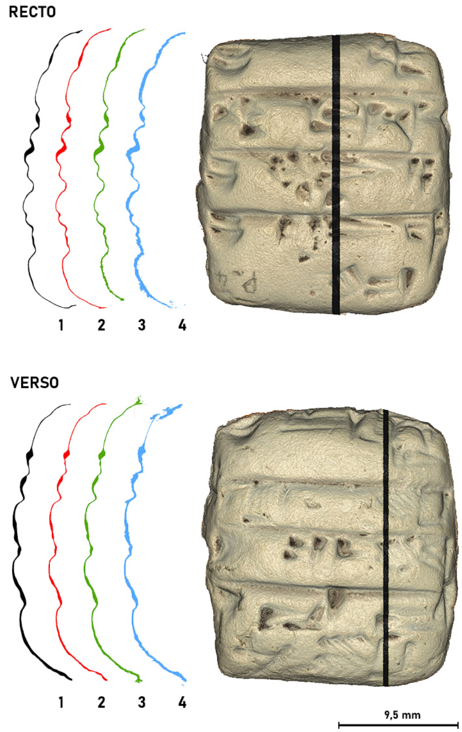


Figure 10
Colour per vertex of verso side acquired with the different passive sensors

Figure 11
On the left, a comparison of point clouds sections generated with different datasets: 1) by "SCAN in a BOX", 2) by Nikon D810, 3) by microscope Dino Universal and 4) by microscope Dino High Speed. On the right, the point cloud obtained from the Nikon D810, with the positioning of the slice chosen for the comparison

On the other hand, it is necessary to specify that, to pursue the survey primary objective, that is the verifiability of metric data, some key aspects are still to be more rigorously defined. In addition to software house changes to enable the Exif data to be saved, there are several changes required to the calibrator in Figure 2. Firstly, reducing the makers dimensions and spacing will allow more points of known coordinates to be identified.

Moreover, the geometry of the plate could be modified to fit a motorized turntable to facilitate possible tilted-axis acquisitions. However, the 3Dino Plate is suitable for objects up to 2-3 mm thickness, i.e. mainly two-dimensional objects such as coins. In such cases, it would not be necessary to change the geometry of the plate. It should be borne in mind, however, that the use of the plate always requires two sets of acquisitions. The problem of shallow depth of field remains and can really be solved by reshaping the acquisition, e.g. with Focus Stacking techniques, using a micrometric slide to move the optical system. For these reasons, and in order to streamline the acquisition procedures and ensure a more rigorous workflow, the authors are designing a system that involves reformulating the plate geometry in order to adapt it to a rotary table system that makes the object rotate - and not translate - with respect to the sensor.

Although still with limited architectural applications, this experiment showed that, verifying their great accuracy, it is possible to adopt this system for photogrammetric survey of tiny artifacts. Consequently, in further applications, this procedure could be extended to different acquisition scales, such as architectural ornaments and friezes, possibly evaluating the integration of macro optics too.

Despite the problems within the framework of modern micro-technologies, more interesting ideas for the three-dimensional documentation of very small artefacts that would otherwise be difficult to represent prevail from this work in progress.

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NOTES

[1] The cuneiform tablet used as a test is the 3D printing replica in geopolymer of the 724 tablet realized by the +LAB (www.piulab.it - Politecnico di Milano). The original 724 tablet was 3D measured by the 3D Survey Group (Politecnico di Milano). The interdisciplinary research aims to obtain a digital and physical clone of the cuneiform tables with high details and high accuracy for education and scientific purposes (e.g. shared analysis and studies among a team of archaeologists to decipher a text content).

[2] The specific print settings for making the plate are listed below: print used: Creality CR-10 v 1.0; dimensions: bed 300x300 mm x height 400 mm; bed temperature: 50 °C; nozzle temperature: 200 °C; nozzle diameter: 0,3mm; material used: PLA 1,75 mm ± 0,05 mm; layer height: 0,12 mm; infill: 20%; infill pattern: cubic; printing speed: 50 mm/s; approximate time for printing: 13 hours.

[3] To perform a homologous comparison for both active and passive techniques, the procedure was performed in CloudCompare 2.10.2.

[4] The ICP (Iterative closest point) algorithm, because of its iterative nature, can only guarantee the convergence to a local minimum. The error in the final registration is expressed through RMSE, or RMS of the Euclidean distance between the match point pairs of the alignment process. For each ICP iteration the maximum number of matches was set to 50.000 and the number of iterations for the process equal to 60.

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