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PENGUIN 3.0 - CAPTURING SMALL FINDS IN 3D

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ABSTRACT

Archaeological small finds provide a variegated myriad of data of crucial importance to the study of their finding contexts. Anyway, only a close all-around examination can give a full comprehension of their multiple functions. The production of reliable documentation is thus an essential process and this paper illustrates a fast, reliable and easy tool to collect documentation during the excavation season.

The tool, named Penguin 3.0, was developed at the Geodesy and Geomatics Division - Sapienza University, exploits the potentialities of the Occipital Structure Sensor, a low-cost sensor able to rapidly generate reliable 3D models of small objects. This sensor can be connected directly to a mobile device (i.e. smartphone or tablet) and it collects the 3D information of the scanned object in real-time.

The aim of this work is to perform a methodological presentation of the acquisition procedure in order to highlight the pros and cons of using this 3D scanning technology to capture 3D models of archaeological small finds. The step by step acquisition process is fully described with the goal of identifying a standardized procedure able to generate reliable and accurate 3D models.

This new tool introduces the idea of an objective metrical classification of finds and of a not-anthropic graphic and photographic documentation of them. It is thus the first step towards an automatic pre-classification of finds on a broad scale, making free the archaeologist's time and mental energy for the momentum of study and interpretation.

KEYWORDS: Small finds, close range 3D modelling, Structure Sensor

1. INTRODUCTION

It is well known that archaeological small finds provide a variegated myriad of data, which are of crucial importance to the study of their finding contexts. Hence, the production of reliable documentation concerning such small finds is an essential process during archaeological excavations. Nowadays archaeologists usually document them in 2D by proper representations, but the full comprehension of their multiple functions is strictly dependent on the possibility of a close all-around examination. For this reason, the small finds documentation during excavation can be still considered an open problem.

This paper illustrates a proposal for a possible solution, based on an optical tool developed at the Geodesy and Geomatics Division - Sapienza University. This tool, named Penguin 3.0, by exploiting a low-cost sensor, is able to rapidly produce reliable 3D models of small finds, with a reasonable little effort, enabling its systematic application on the field and thus showing some advantages respect to both traditional (illustration) and more recent (for example Structure From Motion) survey techniques. Further details on the modelled objects are made available simultaneously by dedicated software.

Penguin 3.0 can therefore contribute to the comprehension first and the interpretation later of the archaeological small finds, offering not only a tool for the digital preservation of the cultural legacy or for the dissemination of the results towards a wider and more general audience, through, for instance, databases such as Europeana (Pavlidis and Sevetlidis, 2015), but also new possibilities for the research itself, providing new knowledge and insights (Scopigno et al., 2011, Tsiafaki and Michailidou, 2015).

2. THE TOOL: STRUCTURE SENSOR BY OCCIPITAL

The Structure Sensor™ by Occipital™, launched on Kickstarter on September 2013, is the heart of the tool proposed. It is a low-cost and easy-to-use sensor, able to natively collect the 3D coordinates of several points at high frame rate (30 - 60 Hz).

Therefore, according to the definition given in (Boehler and Marbs, 2002), the Structure Sensor can be considered, to all intents and purposes, a veritable 3D scanner. Furthermore, tracking algorithms such as KinectFusion (Izadi et al., 2011), (Newcombe et al., 2011) allow to continually reconstruct the pose of the moving sensor and to fuse the scans of the object captured from new view points as soon as they are acquired, merging them into an overall 3D model easily and practically in real-time. In this way, the Structure Sensor can be used without any difficulties by non-experts in photogrammetry and geomatics data processing since its usage is very similar to that of a traditional video camera. For this reason, the Structure Sensor is quite different with respect to the classic Laser Scanner, expensive and difficult to use for not-expert users, thus allowing an easy real-time indoor 3D reconstruction, and the development of customized applications. Indeed, by simply framing the target object and moving the sensor around it, the operator obtains a metric 3D model in real-time and without the need of providing an external metric scale during the scanning. All the measurements taken on the models are thus immediately in metric units and this is an essential feature to document the archaeological small finds quickly, effectively and in a comprehensive way.

In particular, the Structure Sensor is specifically designed for mobile devices, such as smartphones and tablets, thus making this technology easily accessible to a wider and inexpert public.

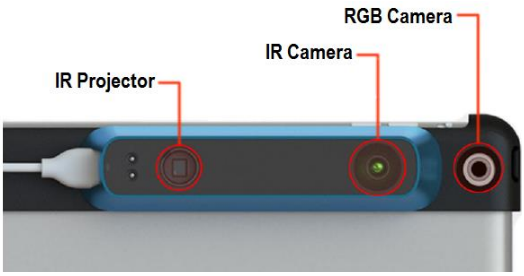

Figure 1. Sensors in the Structure Sensor: the IR projector and the IR camera; the RGB camera is not part of the sensor but it is the one provided with the device (smartphone or tablet) to which it is connected.

Table I. Technical specifications of the Structure Sensor

Technology	Structured Light
Length x Width x Height	119.2 mm x 27.9 mm x 29 mm
Weight	95 g
Minimum Recommended Range	40 cm
Maximum Recommended Range	3.5 m
Depth Field of View (HxV)	58° x 45°
Depth Precision	0.5 mm @ 40 cm (0.15%) 30 mm @ 3 m (1%) (details)
Depth Image Resolution	VGA (640 x 480) QVGA (320 x 240)
Frame Rate	30 / 60 frames per second
Battery Life	3 – 4 hours of active sensing 1000 + hours of standby
Illumination	Infrared structured light projector Uniform infrared LEDs
Operating Temperature	0° to 35° C
Officially Supported OS	iOS
Cost	379 $

To capture the 3D data, the Structure Sensor adopts the *structured light technique*: an infrared laser projector emits a pattern of thousands of invisible infrared dots on the surface of the object/s to be modelled and a frequency-matched infrared camera records how the scene deforms the original pattern, thereby obtaining the 3D geometry (shape and dimensions in metric units) of the objects. The RGB camera is not part of the sensor itself, but it is the one provided with the device used (smartphone or tablet), thing that implies some major practical issues (for further details see Figure 1 and step 4 of the acquisition procedure).

For all the features described above (see also Table I) such as the low-cost, accuracy (from few mm to few cm), easiness and rapidity to use, the Structure Sensor represents a useful 3D scanning system for the modeling of archaeological small finds characterized by a size greater than 10 cm. Concluding, the low-cost of this tool allows more operators to work simultaneously, thus speeding up the documentation process.

3. STEP BY STEP 3D MODEL ACQUISITION PROCEDURE

The following steps describe a general procedure that a generic user should follow to capture a 3D model of an archaeological small find with the Structure Sensor.

1. **Equip a mobile smart device** (officially supported models[1]: 9.7-inch iPad Pro – recommended -, iPad Air, iPad Air 2, 12.9-inch iPad Pro, iPad mini 2, iPad mini 3, iPad mini 4, iPad 4th generation, iPhone 6) **with the Structure Sensor using the mounting bracket**.
2. **Connect the Structure Sensor to the tablet using the Lightning Cable.**
3. **Download a 3D scanning app for the Structure Sensor**. So far, the tool proposed has been tested with the Scanner app provided directly by Occipital inside the Structure Software Development Kit (SDK) samples and available on the Apple Store (https://itunes.apple.com/it/app/scanner-structure-sensor-sample/id891169722?mt=8).
4. **Calibrate the Structure Sensor**. This is the first important step. Since the Structure Sensor does not have its own colour camera, the 3D scanning applications leverage the iPad colour camera in order to texturize the 3D models. Therefore, considering that the object geometry and the texture are caught from two different points of view, it is necessary to calibrate the precise alignment between the Structure Sensor and the iOS device camera in order to accurately overlap the 3D and colour data.
   The Calibrator app provided by Occipital is specifically designed for the Structure Sensor bracket accessory. In particular, this application implements a stereo camera calibration, allowing the user to automatically acquire several pairs of images both with the Structure Sensor infrared camera and the iPad colour camera.
   Simply, the user should slowly move the device, pausing occasionally and framing complex and bright scenes, in order to permit the app to match the same features on both the images, that are visualized in real-time side by side on the tablet screen.
   The feature detection stage ends when a sufficient number of features has been extracted; at this point the app allows to refine manually the calibration quality (only for the horizontal component), until the images are not perfectly overlaid. The calibration parameters found will be adopted in all the apps that use the Structure Sensor and will be stored in the sensor memory until the next calibration.
   The Calibrator app requires a functioning internet connection to compute and save the sensor calibration.
   In addition, the calibration should be carried out in a bright area, uniformly illuminated by a natural day light, otherwise it can compromise both the calibration and the overall 3D scanning results[2]. It is strongly recommended to perform the calibration at the same distance that will be used during the 3D scanning process.
   In conclusion, the calibration should be performed every time the Structure Sensor is mounted and in general before carrying out every new scanning session.
5. **Ensure the object dimensions are suitable for scanning (with the Structure Sensor).** In order to be scanned with the Structure Sensor, the object should have dimensions ideally between 10x10x10 cm and 100x100x100 cm. The archaeological small finds generally do

[1] The Structure Sensor can operate also with Android mobile devices and laptop/desktop machines using Mac OS X, Windows or Linux operating systems, but it is usable more easily with the Apple™ tablets.

[2] A good calibration is in fact fundamental not only to obtain textures of good quality, but also for a successful outcome of the object scan, since it can influence the correct functioning of the tracking (for more details, see step 8).

not show always the right size and a check is always recommended. Large objects need more scanning sessions, respect to one single scan and the obtained 3D models should be registered (aligned) and merged in a post processing stage using standard algorithms (i.e. Iterative Closest Point (ICP) (Besl, P. J. and McKay, 1992)).

6. **Set up the scanning environment.** Since the Structure Sensor is based on infrared light, it is sensitive to direct sun light and indeed it gives best results, in term of both 3D reconstruction and texture quality, with bright uniform artificial light. Regarding the target object, it should be mounted on a pedestal placed on a smooth and flat surface in order to facilitate the tracking. Finally, a wide area should be available around the object to acquire all its sides.
7. **Setup the scanning volume**. Inside the 3D scanning app, the scanning volume (visualized on the iPad screen by exploiting the Augmented reality potential of the Structure Sensor) must cover the target object.
   The operator should set up the dimensions of the scanning volume considering the object size. In order to obtain a most accurate 3D model, it is strongly recommended not to waste resolution and thus the scanning volume should be just a little bit wider than the object size.
8. **Scan the object**. The object must be captured from different points of view in order to reconstruct a complete 3D model. Therefore, the user must slowly move around the target following a 360° path including the top and the bottom. Generally, the needed scanning time is around a few minutes, depending on the object shape and complexity. Furthermore, the scanned model appears directly on the screen and allows the user to check in real-time the model quality and to consequently move the sensor in order to scan again the problematic areas and filling the model holes. In particular cases, for concave objects such as vessel, the operator should scan both the exterior and the interior (if the size of the vessel opening allows it) in order to model the inner volume.
   Nevertheless, it is relevant to notice that the 3D scanning apps can lose the tracking of the object. The tracking is the process by which a 3D scanner is able to lock on and reliably estimate its own motion in relation to the object being scanned. The tracking loss can happen, for example, when the user moves too fast or when the object to be scanned is too small. However, it is also important to consider the possibility that the object could not be suitable for scanning with the Structure Sensor (for example if it has too tiny details, or a dark/shiny surface).
   Finally, it is worth remarking once again the importance of the calibration (see step 4) for the tracking process too.
   All these features make the scanning process easy and user friendly.
9. **First check of the resulting model**. Once the scan is completed, the 3D scanning apps generally provide the possibility to inspect the resulting model directly on the tablet screen and to export it via mail and/or cloud as a texturized meshed[3] model.
10. **Clean the model**. Once the model is downloaded, the pedestal should be removed from the final mesh and the related hole filled with a standard 3D mesh/point cloud processing software, such as CloudCompare (Girardeau-Montaut, 2017) or MeshLab (Cignoni et al., 2008).
   For example, with the Interactive Segmentation Tool of CloudCompare, it is possible to remove the points (or triangles) falling inside (or outside) the border of the 2D polygon defined interactively by the user.
   Then, to close the base of the model, the user can cut a thin section in correspondence of the pedestal hole with the Cross Section Tool. This operation generates a "remaining cloud" on which a planar mesh can be fitted with the Delaunay 2.5D Mesh Tool. Sometimes it is necessary to refine the results by translating downwards the mesh obtained with the Translate/Rotation Tool. Finally, the closing mesh can be merged to the object model.

4. TECHNICAL SPECIFICATIONS AND METHOD OF USE

Concerning the 3D geometry reconstruction, the 3D models obtained show a resolution and an accuracy ranging from a few millimetres to a few centimetres, depending on the overall dimensions of the scanning volume, the acquisition distance and the object features (Ravanelli et al., 2016), (Ravanelli et al., 2017).

The texture reconstruction can be instead less accurate, since occasionally the colour is not perfectly aligned to the 3D geometry in some areas of the model, particularly for those captured at the end of the scanning process (at the end of the 360° path).

[3] A mesh is a collection of vertices, edges and faces that describes the shape of an object.

This behaviour can be explained with a not perfect outcome of the calibration and/or residual tracking errors. Furthermore, the colouring approach used by the Scanner app of Occipital tends to smoothen the texture details so that the texture details of model are lost.

Figure 2. An example of two vases with different dimensions modelled with the Structure Sensor. The most important archaeological quantities are measured (the measurements are expressed in m).

Finally, the Structure Sensor works in the infrared spectrum, so that all the infrared light sources can interfere with its correct functioning, reason for which it cannot be used outdoor in a sunny day. For the same reason this device can show difficulties to reconstruct black (they reduce the power of the pattern signal, absorbing the infrared light) and shiny surfaces (they show a too high amplification of the reflected pattern signal).

5. APPLICATIONS AND OUTPUTS

The 3D model provides all the necessary information to completely describe the archaeological small finds. Furthermore, it allows to take the measurements in a second time, such as the volumetric computation and the study of the sections. All these measurements are expressed in metric units because the proposed tool collects 3D models that belong intrinsically to a metric space.

With the CloudCompare software it is possible to cut the model in one and/or several slices through the Cross Section Tool.

Instead, to compute the volume, the Compute Geometric Measures (Quality, Measure and computation Filter) Tool of the MeshLab software can be used (Barreau et al, 2014), (Cignoni et al., 2008). Anyway, it is essential to underline that only the volume of a closed model (watertight mesh) can be computed. For instance, to compute the volume of a pot, the user must close also the higher opening at an arbitrary level that should be the rim of the shape, repeating the same procedure adopted for closing the pedestal hole. Some results are illustrated in Figure 2.

6. THE 3D OPTICAL SCANNER PENGUIN 3.0 AND ITS UTILITY IN FIELD ARCHAEOLOGY

The device illustrated in this paper has a variety of application in field archaeology, especially when it is included in the regular procedure of excavation and documentation of finds, their contexts, and archaeological monuments in the case of rescue excavations.

6.1. *Small finds and architecture*

Small objects and tools, within a dimensional range comprised between 1 cm and 0.5 m, are the vast majority of finds in an archaeological excavation. They are traditionally documented by means of bidimensional photo and drawings, sometimes added by 3D scanning or modelling. They are sorted by broad functional classes, and studied according to their material (metals, pottery, glass, wood, stone). Shapes and dimensions are used to properly include them in established typologies, as well as other physical and volumetric peculiarities. This latter aspect, the formal one, has for more than a century dominated the criteria of classification in archaeology, while the stuff of which these items are made of, has been only in the last five decades given a scientific attention. Nonetheless, the shape has been by far the dominating criterium for objects classification, while dimensions and especially the 3 dimensions have been relegated aside.

This new tool introduces the idea of an objective metrical classification of finds and of a not-anthropic graphic and photographic documentation of them. It is thus the first step towards an automatic pre-classification of finds on a broad scale, making free the archaeologist's time and mental energy for the momentum of study and interpretation.

Moreover, Penguin 3.0 allows to store finds in a digital archive as they are in their physical (too often inaccessible) storeroom, making them tridimensionally available to scholars in the time of a computer query.

In the case of stone and metal tools, Penguin 3.0 can automatically provide the volume, a previously neglected basic datum to be taken into consideration along with the weight of such items. It may be of invaluable help in the calculation of economic factors, such as raw material needed to produce the object, or facilities necessary to store or carry it.

Penguin 3.0 has also a very important application in architecture as it allows a more careful and reliable modelling of bricks and stones composing walls. This datum is also useful for calculation concerning earthen and pre-classical not modular architecture

6.2. *Pottery*

The applicability area of Penguin 3.0 includes also archaeological ceramics. Documentation and record of pottery finds could be improved in accuracy and speediness by means of this tool. For its technical limits (see section 3 for the allowed dimension range) the application expresses its better performances on items larger than 8 cm.

A seen for the small archaeological finds, pottery is traditionally documented with the projection drawing of profile and front view of the ceramic fragment, usually accompanied by photos. The utilization of Penguin 3.0 optical tool as an integration of such well-established method (in the future a possible substitute of it) allows to catch more accurate and complete data, and open up new perspectives in the study of ceramic finds. Vessels and fragments models are made available to scholars for a thorough study. They can handle their pieces observing them from infinite points of view without actually touching the items. This means that they for the first time can approach pottery in its real tridimensional essence, studying manufacture, capacity, and functions on the ground of a more realistic view.

The high potential of implementation of Penguin 3.0 can be summarized by the following four key strengths.

1. **Optimization of the filing process of pottery records.** The 3D optical scanning of the pottery find, even if the vessel is not complete, gives back a prompt output of its shape, dimensions and surface treatments (slip, decoration, burnishing). If some part of the vase is lacking, the program provides the most plausible reconstruction of the whole shape, making its integration recognizable.
2. **Immediate availability of dimensional data.** The quick indication of vessel dimensions and volume skips complicated manual calculus, with a considerable gain in time and better accuracy. Precise volumetric data allow to go back to vase study, for example measuring its different parts, setting new investigation target in the 3D item itself (manufacturing, tectonic, daily use). As an example, the indi-

viduation of volumetric classes in transport amphorae bears to sketch out, on the one hand, production dynamics and storage potentialities (the real capacity of each vase and quantity of stuff held inside in respect of its final weight), and, on the other hand, may suggest conditions and methods of transport and stockage.

3. **High-fidelity 3D reproduction in short time: rescue archaeology**. Penguin 3.0 realizes a high-fidelity duplicate of the vessel, rather than the ideal and schematic representation of the traditional drawing, that follows graphic conventions that in many cases do not correspond to the real aspect of the find. The agility of the tool and the short fulfilment time of the 3D model make it suitable to being used in emergency excavations and in critical conditions, i.e. during public works of strategic relevance and war scenarios.
4. **Typology and seriation of 3D shapes**. As previously suggested for the Small Finds, Penguin 3.0 3D models of ceramic materials can be collected in an open database connected to a morphology-recognition software. This would actually revolutionise the present approach to pottery, commonly based upon intra-site typologies built up on fragments uniformed by means of traditional drawing techniques. A 3D data base of shape could instead compare real parameters in a more systematic and reliable way (e.g. dimension, rim shape, decoration), and classify finds enrolling them into real productions which share similar typological parameters. This preliminary identification ceramic finds thus only need a final validation by the archaeologist, based upon a complete tridimensional evaluation of each single ceramic item in comparison with all the others included into the database.

7. CONCLUSIONS AND FUTURE PROSPECTS

The proposed tool introduces the idea of an objective metrical classification of finds and of a not-anthropic graphic and photographic documentation of them. The obtained 3D models show a resolution and an accuracy ranging from a few millimetres to a few centimetres, depending on the overall dimensions of the scanning volume, the acquisition distance and the object features.

Due to its low-cost and flexibility of use, Penguin 3.0 is indeed a suitable instrument for a rapid 3D modelling of archaeological small finds, especially when not expert users are involved. Since the technology is very rapidly evolving, other low-cost 3D scanning sensors will likely be available soon; therefore, it will be of interest to update the investigations related to the quality assessment of the 3D models of archaeological small finds.

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