Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2, 311-318, 2018
https://doi.org/10.5194/isprs-archives-XLII-2-311-2018

30 May 2018

3D RECONSTRUCTION-REVERSE ENGINEERING – DIGITAL FABRICATION OF THE EGYPTIAN PALERMO STONE USING BY SMARTPHONE AND LIGHT STRUCTURED SCANNER

F. Di Paola and L. Inzerillo
DARCH - Dept. of Architecture, Polytechnic School, Palermo, Italy

Keywords: Cultural Heritage, Structured Light Scanning, Smartphone, 3D modeling, 3D sculpting, Digital Fabrication

Abstract. This paper presents a pipeline that has been developed to acquire a shape with particular features both under the geometric and radiometric aspects. In fact, the challenge was to build a 3D model of the black Stone of Palermo, where the oldest Egyptian history was printed with the use of hieroglyphs. The dark colour of the material and the superficiality of the hieroglyphs' groove have made the acquisition process very complex to the point of having to experiment with a pipeline that allows the structured light scanner not to lose the homologous points in the 3D alignment phase. For the texture reconstruction we used a last generation smartphone.

Conference paper (PDF, 1181 KB)

How to cite: Di Paola, F. and Inzerillo, L.: 3D RECONSTRUCTION-REVERSE ENGINEERING – DIGITAL FABRICATION OF THE EGYPTIAN PALERMO STONE USING BY SMARTPHONE AND LIGHT STRUCTURED SCANNER, Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., XLII-2, 311-318, https://doi.org/10.5194/isprs-archives-XLII-2-311-2018, 2018.

3D RECONSTRUCTION-REVERSE ENGINEERING- DIGITAL FABRICATION OF THE EGYPTIAN PALERMO STONE USING BY SMARTPHONE AND LIGHT STRUCTURED SCANNER

F. Di Paola, L. Inzerillo

DARCH - Dept. of Architecture, Polytechnic School, Palermo, Italy - francesco.dipaola@unipa.it laura.inzerillo@unipa.it

Commission II/WG8

KEY WORDS: Cultural Heritage, Structured Light Scanning, Smartphone, 3D modeling, 3D sculpting, Digital Fabrication

ABSTRACT:

This paper presents a pipeline that has been developed to acquire a shape with particular features both under the geometric and radiometric aspects. In fact, the challenge was to build a 3D model of the black Stone of Palermo, where the oldest Egyptian history was printed with the use of hieroglyphs. The dark colour of the material and the superficiality of the hieroglyphs' groove have made the acquisition process very complex to the point of having to experiment with a pipeline that allows the structured light scanner not to lose the homologous points in the 3D alignment phase. For the texture reconstruction we used a last generation smartphone.

1. INTRODUCTION

The potential of the new non-invasive and non-destructive alternative technologies to the traditional and invasive ones, currently proposed for the application to cultural heritage, represents a significant example of how distant fields, such as conservation, research, and advanced industry can share a common interest.

Operative procedures and protocols for the enhancement of scientific survey tools, which employ computerised and automatic procedures, are nowadays well-established.

One of the actions with highest priority carried out by the authorities, museum institutions and superintendencies, involves the development of digital methodologies for archiving, recording, and restoration of priceless artefacts, following their deterioration or destruction (Apollonio et al. 2017, Gonizzi Barsanti, 2013, Soile et al., 2013, Wachowiak and Karas, 2009).

The opportunity to produce a scaled and rendered 3D model of a cultural artefact is therefore an advantage for the community.

The Smithsonian X3D project, is another example of best practice in the field of cultural heritage. Its collection includes 137 million artefacts and artworks, only partially accessible to visitors, while the rest is stored and available only to scholars, archaeologists, and professionals.

The aforementioned project aims to carry out the digitalisation of the whole collection, creating a database available to a broader public and allowing an integrated documentation, which would be heterogeneous, shareable, and implementable over time (https://goo.gl/WSYgfz).

In the field of cultural heritage conservation, the digital documentation can serve such purposes as a temporary replacement for the original ones which may be on a loan, under ongoing restoration, subject to theft, or to serve as a fruition device for the visually impaired (Di Paola, et al. 2017; Arbace et al., 2012).

An emblematic example is the recent reproduction in scale 1:3, through CNC machinery, of the Monumental Arch of Palmyra (Syria) near the Temple of Bel, destroyed in 2015 with explosives and jackhammers by ISIS militia.

In this last year, much research (REPLICATE EU Project) has been conducted in order to identify pipelines to achieve 3D archives of museum collections according to low cost and user-friendly methodologies thanks to the SfM process developed for mobile devices (Inzerillo 2017, Poiesi et al, 2017).

However, there are some cases where it is not always possible to use low cost and user-friendly techniques because the features of the object require more sophisticated equipment and expertise.

An example of this is the black Palermo Stone which is an important fragment of hieroglyphic inscription.

To get the 3D acquiry of the stone, not only it was necessary to use a blue structured light scanner, but it was also necessary to experiment the target capture process and implement the acquisition with a smartphone to create the texture.

1.1 Related Work

The traditional analysis and geometric documentation of ancient inscriptions and the physical reproduction of ancient stone is based on invasive and manual operation.

The common practice to study inscribed fragments includes the use of a special type of moisturized paper (squeeze) pressed into the stone, through which the scholars attempt to create an impression of the surface of the inscription (Woodhead, 1992).

Other materials used in the literature for the above process are latex or liquid rubber (Beck, 1963).

These invasive methods involve direct physical contact with the artefact, requiring an analysis of the material degradation of the artwork and an in-depth knowledge of the chemical and physical properties of the material used, as well as the damage it may cause. Therefore, nowadays casting is usually not recommended.

In Italy, however, it is permitted under exceptional cases, regulated by the Ministerial Decree of the 20th of April 2015.

Several experiences proposing systems by non-contact and non-destructive techniques are documented in literature, which can significantly facilitate the daily work of scholars in the field.

Some methodologies describe how to process image data captured using the highlight capture method, the Highlight RTI methodology (Reflectance Transformation Imaging) (http://culturalheritageimaging.org/About_Us/CHI_Team/).

Other approaches are sought involving video sequences or a set of 2D images for reconstructing a three-dimensional scene Liamas, et al., 2016; Lerma and Muir, 2014; Koutsoudis, et al., 2013) or cases which require an expensive and sophisticated 3D

inspection system, such as laser triangulation scanner (Landon and Seales, 2006; http://scann3d.smartmobilevision.com).
There are also some experimental software that include machine vision algorithms which apply page layout analysis, text line extraction, character recognition, and information retrieval (Stanco et ali, 2012).
However, especially when the inscriptions are weathered and practically illegible, the accuracy and detail of the obtained model surface is not high enough for capturing particulars such as letters and symbols.
Furthermore, the design of a digitization system is determined by factors such as the environment in which the object must be accessed and manipulated, the material properties and the fear of damaging the stone.

1.2 Aim and structure of the paper

In this paper we aim to describe the scientific and rigorous workflow of the 3D acquisition and graphical Modeling (Reverse Engineering, Sculpting 3D, Digital Fabrication) with non-invasive digitalization and high information density techniques for a case of extreme condition like that of the Palermo Stone.
The fragment is the largest preserved fragment of a large black diorite stele, which chronicles about 700 years of Egyptian life on both sides and is considered an invaluable and fundamental document for the reconstruction of the most remote Egyptian history. We know other fragments of sure relevance, two of which are preserved in the Egyptian Museum in Cairo and one at the Egyptian Archaeological Petrie Museum of University College, London.
The most significant parts are those related to overcoming the difficulties of acquisition and the reconstruction of the texture. In fact, the first problem to overcome was to help the Spider Scanner to recognize the homologous points.
The rest of the paper is outlined as follows. In Section 2, the Data Acquisition Methodology is presented including a detailed object's description. The section 2.2 is divided in two subsections describing the data processing steps that have been followed and the results: Structured Light Scanner acquisition, SfM one and their comparison.
In Section 3, we present the results of registration and processing steps and the digital sculpture tools used to study a methodology to enhance the reading of the hieroglyphic writing. In the subsection 3.3 we present the 3D printing technique applied to reproduce a fragment of the model stone that played a pivotal role to and favouring the communication to the final users, in particular Egyptologists. In Section 4 we conclude.

2. MATERIAL AND METHODS

2.1 Object's description

The Stele is divided into horizontal bands in turn divided into compartments each containing an inscription in hieroglyphics. In it there are recordings, preceded by a list of names of predynastic monarchs, the Annals of the first five dynasties of the Egyptian history period called Ancient Kingdom (2850-2322 b.C. cy.), from the kingdom of Menes, the pharaoh who unified the Egypt, until then divided into High and Low, to the third pharaoh of the 5th dynasty. The face preserving the earlier annals (of the First to Fourth Dynasties) is traditionally termed the *recto*, while the other face (preserving the annals of the late Fourth and early Fifth Dynasties) is termed the *verso*. It reports year by year (each compartment corresponds to one year), the name of the kings accompanied by that of the mother, the most important events and the height reached by the flood of the river Nile. It also indicates the appropriate donations of land and property made by the kings to the god Ra, to Hathor and to the mysterious Souls of Heliopolis. Its function was probably calendrical and chronological for the benefit of the temple of Phat at Menfi, where it is hypothesized to have been found.
The Palermo Stone is the largest fragment (29 x 44 cm) but, until now it has not been possible to know the measurements of the entire stele (Fig. 1).
The Palermo Stone has become part of the Archaeological Museum "A. Salinas" of Palermo collections since the late nineteenth century. It has been learnt that the ancient work of art was donated by the collector of works of art Ferdinando Gaudiano.
The stone is kept inside a plexiglass case and it is not possible to touch it except through special gloves used by the restorers.
We asked to remove the case and rotate the stone on both sides according with the survey phases.
The challenge was to carry out a survey campaign that was appropriate to the features of the Palermo Stone. It presents a smooth surface of black colour, material with reflective properties, deposits of fine dust, barely visible incisions especially in the recto, logistical difficulties of acquisition and the constraints on access/manipulation. This last aspect is not the least important because we had only one day to make the survey and we needed the supervision of the restorer to turn the stone and workers to dismantle the case.
The information of the Egyptian history of the first dynasties described in to inscriptions have been the focus of countless studies in the century or so since they first came to light.
The document from ancient Egypt has been translated, interpreted by generations of Egyptologists and one of the most authoritative studies is the "Royal Annals of Ancient Egypt by Toby A.H. Wilkinson (Wilkinson, 2000).
Still, there are many doubts and questions concerning the provenance, date and the original dimensions of ancient stele.
For the first time we have acquired it digitally highlighting the undeniable benefits in terms of reliability and management, creating a data bank which is consultable and implementable in relation to conservation and future transmission.

Figure 1: Pictures of *verso* and *recto* of the Palermo Stone.

2.2 Data Acquisition Methodology

The experimentation goal was to realize new tools, to increase the existing archaeological knowledge and to obtain referenced information useful for recording and monitoring the conservation state of the ancient important work of art.
The 3D models, generated using an integrated use of the procedures of *SfM* techniques and a high-resolution 3D scanner

based on blue light technology, provide an accurate graphic documentation and offer new approaches for an innovative fruition in the archaeological field (Schonberger, 2016, Inzerillo, et al., 2013).

2.2.1 Structured Light Scanner: The first experimentation was conducted by using the *Artec's Spider* instrument. Despite the high-performance of this instrument, the application on the stone showed processing difficulties due to the black color of the stone and the impossibility of applying markers on it.
The process started on physical models is defined as reverse Modeling, and the digital resolution up to 0.1 mm for each object was realized using the 3D portable scanning system with a structured light flash bulb, permitting highly detailed digital models to be produced. The 3D model provides an accurate graphical documentation, useful for recording the state of conservation of the work of art.
The survey conducted through the Spider allows you to read and decipher the signs of hieroglyphs through the marks left in the mesh and not in the texture.
The extremely versatile system scans at 8 frames/s; frames are automatically aligned in real-time (it does not require any special markers to be placed on the object being scanned). The process is functional, rapid, and capable of acquiring almost 1.000.000 points⁄s and turned out to be particularly suitable for the geometric dimensional characteristics of the object.

Figure 2: Acquisition phases via 3-D scanning of the Palermo Stone.

The structured light system works with a light source projecting a series of light patterns on the object to be scanned (blue LED). The reflected image is captured by cameras, and from the analysis of the distortion of the pattern, the position is evaluated on each point of the surface to be scanned. The 3D scanner utilises a rather simple scanning procedure: it is sufficient to move uninterruptedly around the object and film it from various angles.
Although the technical characteristics tell about an alleged irrelevance of the camera angle, it is easy to observe how rays, which are perpendicularly incident and/or not tangent, assure a greater final accuracy (Tab. 1).
In particular, due to the specific shape of the object, the global alignment with a single shot strip-run would not have been of immediate determination. That is the reason why a little-acquisitions project has been implemented, on the order of a few tenths of seconds (repeatedly changing the original shooting stations in order to capture data relating to the parts which were initially hidden or in the shade).

Structured Light Scanner	
3D resolution, up to (mm)	0.1
3D point accuracy, up to (mm)	0.05
3D accuracy over distance, up to	0.03% over 100 cm
Texture resolution (mp)	1.3
Colors (bpp)	24
Structured light source	Blu LED
Data acquisition speed, up to	1 mln points / sec.
Exposure time (sec)	0.0005

Table 1. *Artec's Spider* instrument general specs.

In relation to the difficulty encountered, it was decided to build a system of external markers that allowed the instrument to recognize homologous points. The system was made of plywood and cardboard, mounted on a rigid support and adjustable in height (Fig. 2).
The built support is modular, and it does not touch the archaeological find. It can be mounted on a photographic easel and it can be directed in all directions. Thanks to the integration of this system during the acquisition process the instrument did not lose the traceability of the connection points between the frames and, moreover, there was a greater superficial detail in the recording phase (Fig. 3-4).
The greatest difficulties have been encountered on the recto side, where the depth of the signs is extremely superficial and difficult to detect even with magnifying glasses and intense and suitably oriented light sources. In fact, this is the least investigated side due to the difficulty in reading the signs.

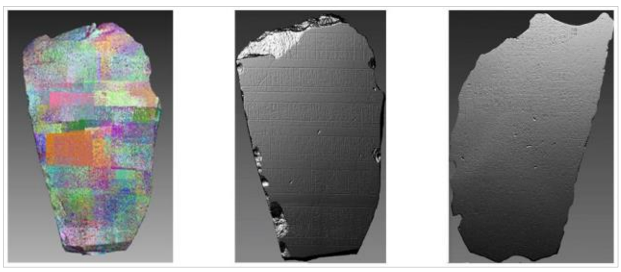

Figure 3: 3D scanning and data registration processing steps: frames alignment.

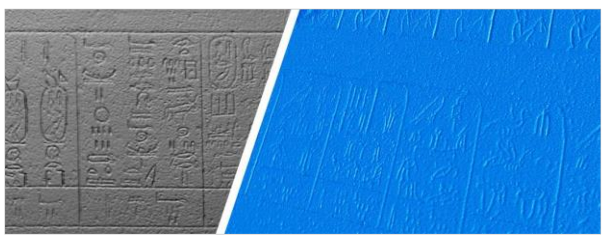

Figure 4: 3D scanning and data registration processing steps: registration and merging point cloud.

2.2.2 Texture reconstruction using by the smartphone

To overcome the problems related to the texture generated by the artec (its texture resolution is 1.3 mp; it is too low for the level of detail required), a dataset was created using a smartphone of the latest generation: *Samsung 8 plus*.
In these last years, smartphone camera technology has made incredible developments with regards to sensor quality and software camera achievement. This has allowed experimentation in the field of photogrammetry for low cost and user-friendly applications (Nocerino et al., 2017, Poiesi et al., 2017, Pintore et al., 2016, Ondruska et al., 2015).
In this paper we have integrate the smartphone photogrammetric 3D model with the light structured scanner one.
To guarantee the colour fidelity we used a X-Rite ColorChecker Passport (CC) target (Fig. 5.a) and for the metric scale we carried out the real distance from the artec 3D model between two columns on the stone and created the corresponding markers as shown in the fig. 5.b.

a b

Figure 5: 5.a X-Rite ColorChecker Passport (CC) target close the stone; 5.b markers points on the S8+ model.

The S8+ camera specs have been used during the camera calibration process. Tab. 2.
The texture obtained from the photogrammetric processing was very well defined both in the shape and in the colours and, having been processed through camera calibration and metric scaling, it is ready to be used on the mesh of the structured light scanner 3D model. (Fig. 6).

Smartphone properties	
Resolution	3024x4032
Make	Samsung
Model	SM-G955F
Focal length	4.2
F-stop	F/1.7
ISO	160
Shutter	1/33
35 mm focal	26

Table 2. S8 plus general specs.

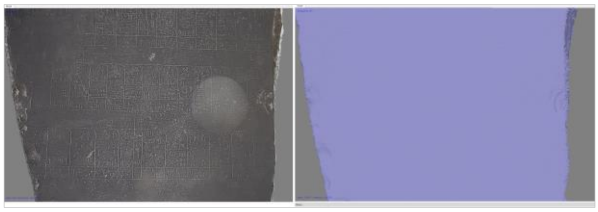

Figure 6: Details of the S8+ 3D model; both texture and mesh.

3. RESULTS AND DISCUSSION

3.1 Registration and processing steps

In the post-processing phase, considering the fragment's physical-material features, we have utilized operational software solutions able to obtain more accurate results in terms of precision of geometric dimensional data and guaranteeing the readability of hieroglyphic writing, with a high degree of geometric correspondence to the real object.
The related proprietary software directly integrates with the scanner (*Artec Studio*, software for professional 3D scanning and data processing) and allows us to use some tools to join all the acquired frames in a single mesh and provide full support for textures and huge raw datasets. The algorithm, in fact, recognizes the geometry of the object (points clouds processing) and allows the correct alignment of the various captured 3D frames to visualize them in a single model (therefore conserving the reference system), eliminating as much as possible the presence of holes and shadows due to back drafts.
The algorithm makes a series of adjustments to the relative spatial positions on the basis of couples of homologous points defined by the user (by means of surface matching algorithms, particularly the *ICP* algorithm - Iterative Closest Point - which aligns the common parts of adjacent scans through the minimisation of the distance between them). After that it automatically aligns two or more scans according to the points arrangement.
The high-quality 3D digital models are responsive to the complexity of the geometric-form of the analysed objects, and the digital collection reproduces the decorations in a good organic form. The collected data so far are a great start for deepening the existing knowledge from the archaeometric to the conservative point of view.
We encountered difficulties for the texture reconstruction too. Indeed, the one carried out by the Spider, is not readable due the dark color. To overcome the problem, we decided to process the Palermo Stone by SfM techniques, aligning the two models in MeshLab and using the merged mesh to reconstruct the texture using the data set.

3.2 Digital sculpture tools

In the field of Computer Graphics, the 3D interactive digital sculpture techniques of mesh models represent the current status of the software evolution art in the field of the organic modeling of free-form complex surfaces.
The tools available for implementation allow the user to interactively carve or paint 3D models enriching their geometric or superficial detail, showing potentialities measured in terms of quality, precision and speed, in the drafting of the graphic compositions and the versatility of management and space control.
There is no doubt about the opportunity of exploration, contaminations, relations, measurements and information,

supplied by the continuous evolution of expeditive and automatic procedures in the use of various products of the informatics era. In this lively experimentation, the progress of the culture of representation tools leads the experts to a specialised level of drawing techniques knowledge, revealing increasingly stimulating multidisciplinary application fields, especially in the field of cultural heritage, valorisation and protection.
The panorama is rich and varied, often generating difficulties in choosing the more specific software according to personal needs and requirements of a high level of applied knowledge. This panorama offers different solutions of CAD platforms with interfaces which maximise effectiveness and flexibility of the work stream. We used the *MudBox* work area to edit the acquired mesh (Fig. 5).
Dialog and library access boxes, navigation palettes rich in icons, and tree-structured drop-down menus allow easy and more rapid web surfing and fast object manipulation through the addition, removal or manipulation of virtual clay layers, fostering the interaction among different format files and an extraordinary control of the detail figurative level.
With reference to the latter, which is linked to the variable control of the surface detail level, one of the most significant innovations in the field of contemporary computer graphics is the introduction of subdivision surfaces (sub-d) (Fig. 6).
These are very important, particularly for the organic modeling of morphologically complex models, because they allow the subdivision of polygons and edges of any mesh surface through specific approximation algorithms (among the most famous: *Catmull-Clark*, *Loop*, *Butterfly*, *Kobbelt*), turning it into another surface entirely made of quadrangular or triangular polygons. These polygons, taken together, form the control cage of the resulting polyhedral surface, can easily be locally modified. This representation technique has great applicability in the field of entertainment software design, but also in the architecture and industrial design fields.
The digital sculpture tools (*Refine*, *Remesh*, *Amplify*, *Adjust falloff*) played a pivotal role to study a methodology to enhance the reading of the hieroglyphic writing. Particularly, the Amplify tool was very useful for designing, detailing, and further accentuating existing differences in the affected vertices in relation to each other by moving them away from a common plane (Fig. 7).
Non-invasive experimental use of methodologies and innovative tools have been developed for analytical procedures of geometric dimensional data, restoration, and monitoring. The use of these tools, employed by these three-dimensional metric measurement techniques, turned out to be suitable for the geometrical characteristics of the subject matter of the research, boasting remarkable productivity and high precision standards when compared to the equipment of the past.
With minimal non-invasive interventions, the survey maintained the entirety and the authenticity of the historical-artistic heritage, highlighting the undeniable benefits of the digital process in terms of reliability and management, creating a data bank which is consultable and implementable in relation to conservation and future transmission (Papadaki et al., 2015).

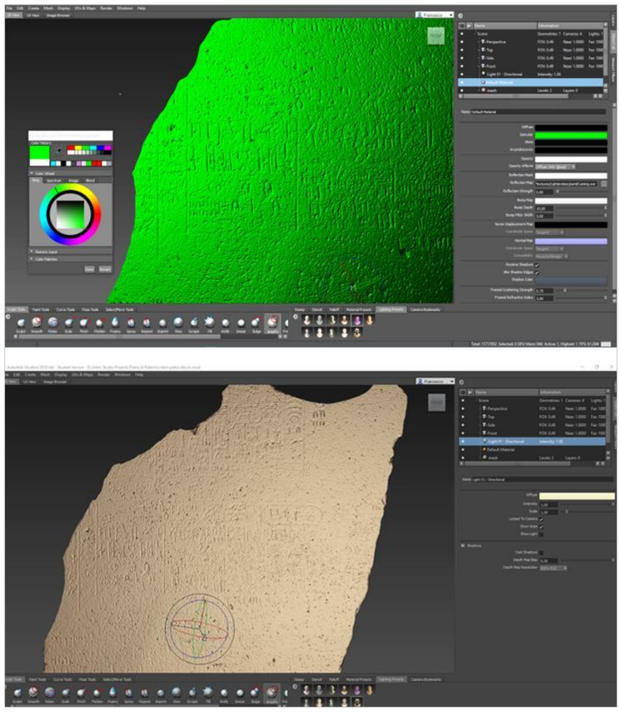

Figure 5: 3D digital model of Palermo Stone; use of sculpting and lighting tools able to guarantee the readability of hieroglyphic writing.

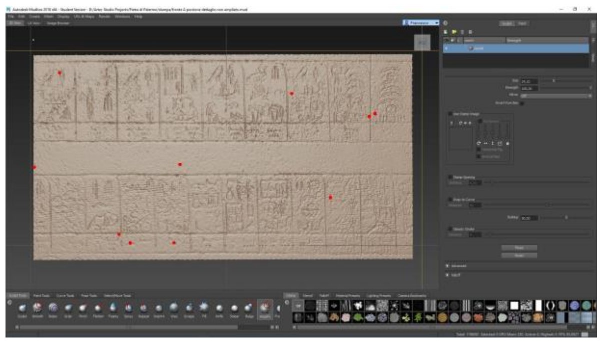

Figure 6: The digital sculpture tool *Amplify* to enhance the reading of the hieroglyphic writing.

Figure 7: Surface detail of the Palermo Stone. Comparison between the photo and the mesh.

3.2 Digital fabrication

Encouraged by the results, we decided to get the 3D print of the Stone. We used a 3D printer and to reproduce one of the most representative parts of the Stone.
The features of the printer did not allow us to print the entire Stone due to the smallness of the hieroglyphics that would not have been visible in the final print (Inzerillo and Di Paola, 2017) (Figs. 8-9) (Table 3).
The 3D printer used in our laboratory is the professional, compact Italian Delta 2040 designed by WASProject that has a heated extruder mounted on a delta robot type structure, a work plan, a group of coils and a heated room that allows maximum print sizes of 200x200x400 mm.
Controlled temperature ambience and amortized bowden guarantee a controlled shrink of the material and better results in the final print.
For the 3D printing, we used a rapid prototyping process (RP) with FDM additive technology. The thermoplastic polymer used for 3D printing is the polylactic acid, better known as PLA, generated by the fermentation of corn.
To print our model we have imported the file within a Computer Aided Manufacturing (CAM) software that allows us to set the print parameters and to define critical areas.

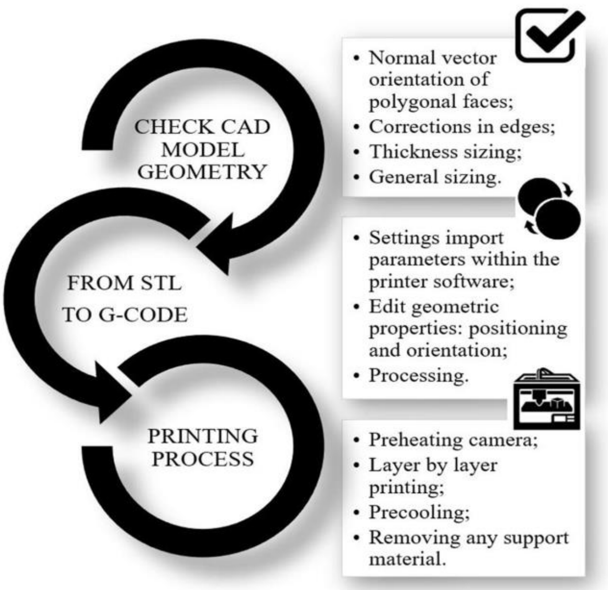

Figure 8: From check model to printing process.

There are many different types of preparation softwares to print commonly said slicers; among the open source, the best known slicing tools are: Cura (developed by UltiMaker) and Repetier-Host (developed by Hot-World GmbH).
For our application we used the last release of Cura platform.

Machine Setting	Basic/Advanced parameters
Layer height	0,1 mm
Shell thickness	1.2 mm
Top/bottom thickness	1 mm
Fill Density	100 %
Printing temperature	210 °C
Build Plate temperature	50 °C
Diameter	0.4 mm
Flow	100%
Enable retraction	active
Print speed	70 mm/s
Travel speed	120 mm/s

Table 3. Setting print parameters.

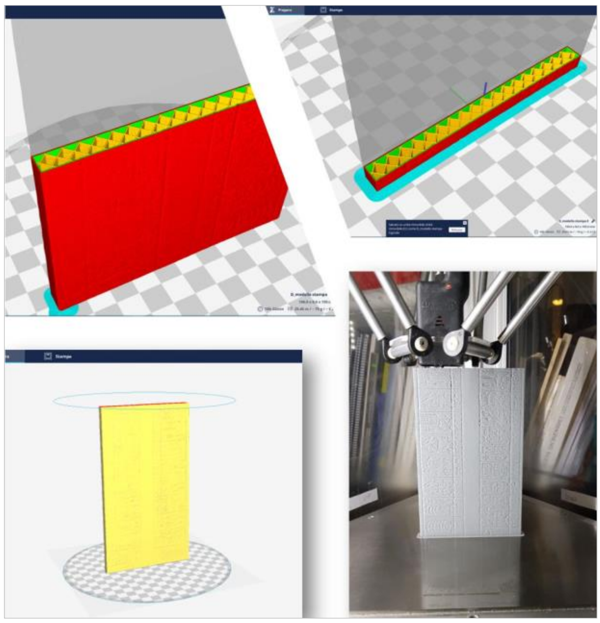

Figure 9: The creation of G-Code file and print phase of object.

4. CONCLUSIONS

This paper presented an experimental workflow aimed at overcoming the difficulties linked to an artefact with so much complexity both under the shape and the material aspects.
The experimental methodology that has been used, shows that the integration of the different 3D survey techniques allow carrying out a 3D model characterized by high mesh and texture resolution. We can conclude that the integration of the light structured scanner and smartphone is a new milestone in innovative survey systems in cases of small objects with high shape and colour complexity.

ACKNOWLEDGEMENTS

This research has received funding from the European Union’s Horizon 2020 Programme, SMARTI ETN, under the Marie Curie-Skłodowska actions for research, technological

development and demonstration, under grant agreement number 721493.
The authors are really thankful to the Head of the Archaeological Museum, Dr Francesca Spatafora, the web designer Dr. Sandro Garrubbo and the archaeologist Dr. Elena Pezzini and all the employees of the Salinas Museum.
Thanks to the results of the digital survey, a collaboration has been undertaken with the Egyptologist Francesco Tiradritti (Director of the Italian Archaeological Mission to Luxor) with the purpose to answer questions and make decisions on specific issues including the ascription of fragments, the dating of the inscriptions, the identification of the place of origin, the identity of the letter cutter and the analysis of the lettering techniques.

REFERENCES

Apollonio, F.I., Ballabeni, M., Bertacchi, S., Fallavollita, F., Foschi, R., Gaiani, M., 2017. From documentation images to restauration support tools: a path following the Neptune Fountain in Bologna design process. *Int. Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. XLII-5/W1, pp. 329-336.
www.dxomark.com/category/mobile-reviews/ (last access: Apr 2018)

Arbace L., Sonnino, E., Callieri, M., Dellepiane, M., Fabbri, M., Iaccarino Idelson, A., Scopigno, R., 2012. Innovative uses of 3D digital technologies to assist the restoration of a fragmented terracotta statue, *Journal of Cultural Heritage*, 2012, vol. 14 (4). http://dx.doi.org/10.1016/j.culher.2012.06.008.

Barmpoutis, A., Bozia, E. and Wagman, R. S., 2010. A novel framework for 3d reconstruction and analysis of ancient inscriptions. Machine Vision and Applications, Vol. 21(6), pp. 989–998.

Beck, C. W., 1963. Synthetic elastomers in epigraphy. American Journal of Archaeology pp. 413–416.

Chen, Y., & Medioni, G. (1992). Object modelling by registration of multiple range images. Image and vision computing, Vol. 10(3), 145-155.

Cornelis, K., Pollefeys, M., Vergauwen, M. and Van Gool, L., 2001. Augmented reality using uncalibrated video sequences. In: 3D Structure from Images SMILE 2000, Springer, pp. 144–160.

Crandall, D., Owens, A., Snavely, N., Huttenlocher, D., 2013. Discrete-continuous optimization for large-scale structure from motion. IEEE Trans. Pattern Anal. Mach. Intell. (PAMI). http://www.cs.indiana.edu/~djcran/papers/disco13pami.pdf (accessed 21.01.15).

Di Paola, F., Milazzo, G., Spatafora, F., 2017. Computer Aided Restoration tools to assist the conservation of an ancient sculpture. The colossal Statue of Zeus enthroned, *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XLII-2/W5, 177-184,
https://doi.org/10.5194/isprs-archives-XLII-2-W5-177-2017

Gaiani, M., Remondino, F., Apollonio, F.I., Ballabeni, A., 2016. An Advanced Pre-Processing Pipeline to Improve Automated Photogrammetric Reconstructions of Architectural Scenes. *Remote Sensing*, Vol. 8(3), 178.

Georgopoulos, A., Ioannidis, C. and Valanis, A., 2010. Assessing the performance of a structured light scanner. In: *Commission V Symposium. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. 38(5), Citeseer.

Gonizzi Barsanti, S. and Guidi, G., 2013. 3d digitization of museum content within the 3d icons project. I*SPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences* II-5/W1, pp. 151–156.

Inzerillo, L., 2017. Smart SfM: Salinas archaeological Museum, in: Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci., Vol. XLII-2/W5, 369-374,
https://doi.org/10.5194/isprs-archives-XLII-2-W5-369-2017.

Santagati, C., Inzerillo, L., Di Paola, F., 2013. Image-based modeling techniques for architectural heritage 3D digitalization: limits and potentialities, in *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XL-5(W2): pp. 550-560.

Inzerillo L., Di Paola F., 2017. From SfM to 3D Print: Automated Workflow addressed to practitioner aimed at the conservation and restoration. In: *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.*, XLII-2/W5, 375-382,
https://doi.org/10.5194/isprs-archives-XLII-2-W5-375-2017.

Koutsoudis, A., Vidmar, B., Ioannakis, G., Arnaoutoglou, F., Pavlidis, G.,Chamzas, C., 2013. *Multi-image 3D reconstruction data evaluation.* J. Cult. Herit., Vol. 15 (1), 73-79.

Landon, G. and Seales, W., 2006. Petroglyph digitization: enabling cultural heritage scholarship. *Machine Vision and Applications*, Vol. 17(6), pp. 361–371.

Lerma, J. L. and Muir, C., 2014. Evaluating the 3d documentation of an early christian upright stone with carvings from Scotland with multiples images. *Journal of Archaeological Science*, Vol. 46, pp. 311–318.

Llamas, J. Lerones, P.M., Zalama, E., Gómez-García-Bermejo, J. 2016. Applying Deep Learning Techniques to Cultural Heritage Images Within the INCEPTION Project. EuroMed 2016: Digital Heritage. Progress in Cultural Heritage: Documentation, Preservation, and Protection pp 25-32, Nicosia, Cyprus, October 31 -- November 5.

Nocerino, E., Lago, F., Morabito, D., Remondino, F., Porzi, L., Poiesi, F., Rota Bulo, S., Chippendale, P., Locher, A., Havlena, M., Van Gool, L., Eder, M., Fötschl, A., Hilsmann, A., Kausch, L., Eisert, P., 2017. A smartphone-based 3D pipeline for the creative industry – The REPLICATE EU Project. Int. Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XLII-2/W3, pp. 535-541.

Papadaki, A.I., Agrafiotis, P., Georgopoulos, A., Prignitz, S., 2015 Accurate 3d Scanning of Damaged Ancient Greek Inscriptions for Revealing Weathered Letters. ISPRS-International Archives of the Photometry, Remote Sensing and Spatial Information Sciences, Vol. XL-5/W4, 25-27 February 2015, Avila, Spain, pp. 237-243.
doi:10.5194/isprsarchives-XL-5-W4-237-2015

Pintore, G., Garro, V., Ganovelli, F., Gobbetti E., Scopigno, R., 2016. Fast Metric Acquisition. In Vision, Modeling, and Visualization (2016) Eurographics Proceedings

Poiesi, F., Locher, A., Chippendale, P., Nocerino, E., Remondino, F. and Luc Van Gool. 2017. Cloud-based collaborative 3D reconstruction using smartphones. In: *Proceedings of the 14th European Conference on Visual Media Production (CVMP 2017) (CVMP 2017). ACM*, New York, NY, USA, Article 1, 9 pages.
DOI: https://doi.org/10.1145/3150165.3150166

Ondruska, P., Kohli, P., Izadi, S. 2015. Mobile Fusion: Real-time Volumetric Surface Reconstruction and Dense Tracking On Mobile Phones. In: *IEEE Transactions on Visualization and Computer Graphics*, Volume: 21, Issue: 11, Nov. 15 2015.
DOI: 10.1109/TVCG.2015.2459902

Scann3D, 2018. http://scann3d.smartmobilevision.com – last access: Apr 2018.

Schonberger, J.L., Frahm, J.-M., 2016. Structure-from-Motion Revisited. Proc. of IEEE *Computer Vision and Pattern Recognition.*

Soile, S., Adam, K., Ioannidis, C. and Georgopoulos, A., 2013. Accurate 3d textured models of vessels for the improvement of the educational tools of a museum. I*SPRS-International Archives of the Photometry, Remote Sensing and Spatial Information Sciences*, Vol. 1(1), pp. 211–217.

Stanco F., Tanasi, D., Guarnera, G.C. and Gallo, G., 2012. Automatic classification of decorative patterns in the minoan pottery of kamares style, in Book: *Pattern Recognition and Signal Processing in Archaeometry: Mathematical and Computational Solutions for Archaeology*, C. Papaodysseus, Ed., pp. 186–211, IGI Global, Hershey.

Wilkinson, Toby A.H. 2000. Royal *Annals of Ancient Egypt. The Palermo Stone and its Associated Fragments*, IBT Global, London.

Wachowiak, M. J. and Karas, B. V., 2009. 3d scanning and replication for museum and cultural heritage applications. Journal of the American Institute for Conservation, Vol. 48(2), pp. 141–158.

Woodhead, A. G., 1992. The study of Greek inscriptions. Bristol Classical Press.

Papadaki, A. I., Agrafiotis, P., Georgopoulos, A., and Prignitz, S., 2015. Accurate 3D Scanning of damaged ancient Greek inscriptions for revealing weathered letters, Int. Arch. Photogramm. *Remote Sens. Spatial Inf. Sci.*, XL-5/W4, 237-243, https://doi.org/10.5194/isprsarchives-XL-5-W4-237-2015.