3D SURVEY AND DATA PROCESSING OF BOLIVIAN ARCHAEOLOGY: THE RITUAL RECEPTACLE FROM TIWANAKU

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ABSTRACT:

The archaeological site of Tiwanaku is among the most important examples of Bolivian archaeology and UNESCO World Heritage Site since 2000. This works reports a geomatic-based surveying and modelling methodology applied to a ritual receptacle excavated from the semi-subterranean temple in the archaeological complex. A high-resolution 3D survey was conducted through structured-light projection scanning and post-processing operations were carried out to emphasize surface details. Most of the operations were conducted in open-source software, with the aim to establish a quick and repeatable methodology to be applied to similar case studies. The final outputs, consisting of geometry projections (unrolled meshes), digitally enhanced surfaces and vector graphics can support the work of archaeologists in interpreting the iconography depicted on the receptacle and to conduct further studies to shed light about culture and religion of the civilization that inhabited Tiwanaku.

1. INTRODUCTION

1.1 Geomatic survey and 3D modelling in Archaeology

Geomatic surveying techniques are increasingly being used in archaeology for a variety of purposes. In addition to the documentation of finds, three-dimensional models of archaeological artifacts can also be used to perform post-processing operations in a digital environment with several aims. Just to mention a few applications, through the processing of 3D data related to archaeological pottery, geometric projections of the objects can be made in order to reveal the sequence of painted decorations on vessels (Rieck et al., 2013; Liu et al., 2017). For other objects, such as engraved cuneiform tablets, algorithms of surface enhancement have been applied, which, coupled with digital projection of shadows and lights at different angles, allow the engravings to be inspected more effectively and thus to better interpret the inscriptions in philological studies (Francolini et al., 2018).

Among the techniques adopted for 3D surveying of small archaeological objects to obtain a high-fidelity digital model, close-range or macro digital photogrammetry and structured light projection scanning are widely used. The former technique, nowadays principally implemented in Multi-View Structure-from-Motion photogrammetric software, is highly appreciated for its relatively short image acquisition time and for the versatility and affordability; in fact, it is often necessary to conduct the survey in a short time and with low budgets. 3D models obtained with this technique can reach sub-millimetre 3D resolutions and feature photo-realistic textures, but it is not always possible or easy to render the most imperceptible surface features at a sufficient level of detail, which is often required for heritage properties. In fact, for limited size objects or for very detailed surfaces, structured light projection scanning is often preferred, or the integration of the two techniques.

1.2 Structured-light projection scanning

3D scanning technologies based on structured-light projection allow for extremely high accuracy. The functioning principle of these scanners is based on the projection of a light pattern (or code), consisting of stripes or points. The pattern is projected onto the object surface and it is distorted by the interaction with its geometry. The distorted pattern is detected by 1 or more CCD sensors in the scanner at different positions with respect to the pattern projector, capturing a sequence of frames as in a video recording. As a result, the acquisition of frames from multiple viewpoints allows the identification of the 3D coordinates of the pattern points and, consequently, of the object geometry, thanks to the triangulation principle (Figure 1).

The accuracy of this type of scanners can reach up to the micrometre level, according to the instrument and to the measuring range.

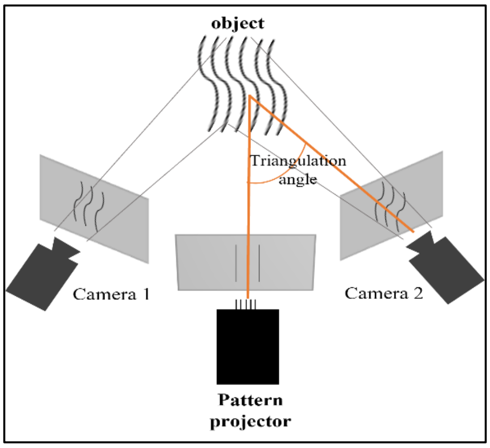

Figure 1. Schematic representation of structured light projection scanning functioning principle

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1.3 The archaeological complex of Tiwanaku

The archaeological site of Tiwanaku is one of the most important examples of ancient Bolivian heritage. Located near the basin of Lake Titicaca, at the border with Peru, it became a UNESCO World Heritage Site in 2000 for the presence of invaluable evidence of the ancient civilizations that inhabited this area. Regarding the dating of the site, after archaeological interpretations and scientific analyses including Radio-carbon dating (Augustyniak, 2004), it has been hypothesized that here was founded, developed and finally culminated, an Andean civilization that was based from around 100 BC to 1100 AD (Rodriguez, 2000; Janusek, 2004 & 2008.)

After the development of Tiwanaku Ceremonial Center, which highlights the religious characteristics of the architectural complexes enclosed in the spaces occupied by the buildings, a slow loss of significance in the thematic contents related to its functionality has occurred. The centre, which held important political and social as well as cultic roles, over a long period of time increasingly became an isolated religious complex, gradually giving way to a growing imperial system, which was fully manifested by the Wari expansion into the Lake Titicaca basin and the subsequent export of its cultural model throughout the area of present-day Peruvian territory, as well as parts of Bolivia.

The last period of Tiwanaku's occupation dates to the 12th century, a time when its distinctive functions as a ceremonial center were lost, favoring its use as a necropolis.

In addition to archaeological and other scientific surveys, remote sensing and geomatics techniques have been employed within the archaeological site. Some recent work involving the use of satellite and drone imagery has provided a better understanding of the morphology and features of the Tiwanaku area through Digital Terrain Models and multispectral imaging (Pérez González, 2020; Lasaponara & Masini, 2014).

Among the ancient vestiges found in Tiwanaku is the famous "Gate of the Sun," an arch-shaped megalith carved from a single block of stone. This giant structure, about 3 meters high and 4 meters wide, features 48 blocks of engravings depicting figures and symbols that have yet to be fully deciphered and understood. The very function of this mega-structure is still not entirely clear.

In addition to the "Gate of the Sun", other important finds have been discovered within the archaeological site, such as the Bennett and Fraile monoliths and the *Chachapuma* basaltic sculpture. Some of these artifacts are preserved at the lithic museum adjacent to the archaeological site (https://tiwanaku.gob.bo/museos/), where the basaltic ritual receptacle, case study of this paper, is also kept.

2. THE BASALTIC RECEPTACLE FROM TIWANAKU SEMI-SUBTERRANEAN TEMPLE AND THE OBJECTIVES OF THE SURVEY

Inside the lithic museum is present the basaltic receptacle case study of this research, originally located in the semi-subterranean temple near the Kalasasaya Temple. The ancient religious architecture (Figure 2), presenting a rectangular structure and made of red sandstone blocks, was discovered in 1960 by former *Centro de Investigaciones Arqueológicas en Tiwanaku* (CIAT). Below the emerged part, there is an underground court (28.5 x 26 meters) in which 175 carved anthropomorphic heads were found embedded in the inner walls (Sanginés, 1981). Here the basaltic receptacle was also excavated, before being transferred to the lithic museum.

Figure 2. Kalasasaya temple and semi-subterranean Temple

The manufact is a conic-shape object carved from a basaltic block (maximum Ø 481.9 mm, average height 156.2 mm), presenting a hollow in the central part with an average depth of 105 mm. It was discovered in 1960 during an excavation lead by archaeologist Gregorio Cordero Miranda, as reported by Sanginés (1981).

The most fascinating characteristic of this object is the fact that the receptacle is engraved all around its perimeter and on the topside. The engravings feature geometric motifs, anthropomorphic and zoomorphic figures, seen in other religious architectures and sculptures found in the surrounding area, and ascribable to the Andean religion symbolism of the civilization that inhabited Tiwanaku (Rodriguez T., 2018; Viau-Courville, 2014).

From the state of conservation point of view, the receptacle presents many scratches and fractures all over its surface, some of which are particularly wide and have compromised the reading of the engraved figures in their correspondence. Several figures are almost unrecognizable, especially in the depiction of the cephalic ornaments which, as reported in the literature, should also refer to plants specific of the traditional medicine.

Figure 3. The basaltic receptacle

The motivation behind this research stems from the need to shed light on the archaeological site of Tiwanaku, many aspects of which have yet to be clarified. The symbolism depicted on this Bolivian receptacle is present in other artifacts discovered within the site but the literature regarding this specific object is still scarce. For these reasons, it was chosen to employ 3D surveying and modelling techniques on the receptacle in order to provide new tools for archaeologists in the interpretation of the figures engraved on the object, and thus to define its functional and symbolic aspects.

From an operational point of view, the objectives pursued were as follows:

1. To realize a very high-resolution 3D reconstruction of the engraved receptacle.
2. To conduct further post-processing operation out of the 3D model such as unrolling, surface digital enhancement and vector extraction, aimed at emphasizing the surface details of the object.
3. To realize further 3D products, to be used as a digital aim in interpreting the religious iconography depicted on the manufact.

3. 3D SCANNING: DATA ACQUISITION AND POST-PROCESSING OPERATIONS

The three-dimensional survey of the basaltic receptacle was conducted in 2014 by DICAM Department, University of Bologna, contextually with different geomatic and topographic surveys carried out at Tiwanaku archaeological site (Bitelli et al., 2020).

3.1 3D model generation

A structured-light projection scanner was employed for the receptacle, the Artec scanner *MHT*, characterized by a nominal accuracy of up to 0.1 mm. The instrumental working distance is between 0.4 and 1 m, acquiring up to 16 frames per second. At an interval set by the algorithms employed by the proprietary *Artec Studio* software, used for both scan acquisition and processing, RGB data are also acquired to complete the 3D model with texture.

The acquired geometry data were first registered, employing software registration algorithms. Then, the registered scans were aligned in the same reference system. Finally, the aligned scans were merged to create a triangulated, untextured mesh consisting of 25.3 million polygons and presenting a 3D nominal accuracy of 0.1 mm (Figure 4).

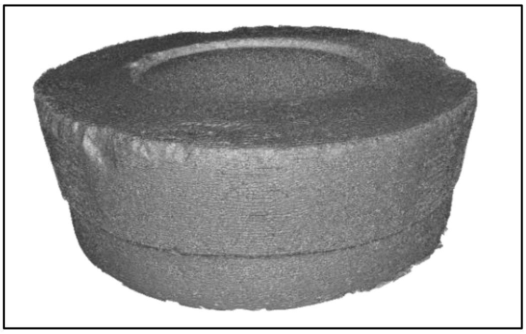

Figure 4. Untextured mesh of the receptacle, 3D nominal accuracy 0.1 mm

A first texture of the model was calculated after the texture frames acquired by the scanner, while a second texture was obtained from images captured with a Leica *V-LUX 20* digital camera (4000x3000 pixels, equivalent focal length 55 mm). This procedure was used to obtain a very realistic texture, through 23 photos representing the object from various viewpoints. The images were registered on the object geometry employing the software's image registration algorithm and then used as source for texture processing.

Two texture libraries and texture maps were then created and coupled with the 3D mesh, but the second option was preferred since the image-based texture was of higher quality and realistic level.

Figure 5. Final textured mesh, 0.1 mm resolution

3.2 Geometry projection

The 3D model of the receptacle was used to perform additional operations to emphasize surface details. First, the object was considered geometrically as a truncated cone. In the proprietary software *Artec Studio*, a geometric primitive of a cone was fitted to the 3D object (Figure 6) in order to extract automatically and accurately the geometrical parameters of the object (half-angle at the cone's vertex, upper and lower diameter) and support an enrolling operation of its lateral surface. The resulting values were: angle 7.7°, lower diameter 481.9 mm, upper diameter 462.1 mm.

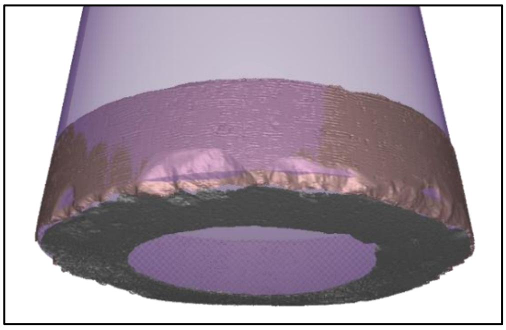

Figure 6. Cone primitive fitted to the receptacle 3D model

The unrolling of the truncated conical surface was carried out using *CloudCompare* opensource software. First, the object was segmented into two separate meshes, one for the perimeter and the other for the topside of the receptacle, since the engraving sets were different. Then, the 3D meshes were imported in the free software *MeshLab* to convert the texture coordinates in per vertex colours.

This operation was done to import in *CloudCompare* vertex-coloured meshes, to be converted into coloured point clouds, considering the mesh vertexes as points; this step was needed since the unrolling in *CloudCompare* is not implemented for solid surfaces. A projection of the two point clouds was then performed setting as geometry values the measurements computed for the cone primitive (half-angle, upper and lower diameter), Y as unroll axis and 0-360° as unroll range. Two planar entities were obtained, sequentially showing the engraved figure sets both for the topside and for the lateral surface. The unrolled point clouds were then remeshed using

MeshLab Ball Pivoting surface reconstruction algorithm. Figures 7 and 8 represent a portion of the unrolled meshes, lower part and topside of the receptacle, respectively.

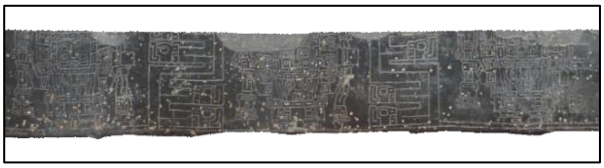

Figure 7. A portion of the unrolled mesh, lower part

Figure 8. A portion of the unrolled mesh, topside

3.3 Mesh segmentation and surface digital enhancement

The unrolled meshes of the lateral surfaces were then segmented to obtain separate portions, each of which representing one engraving block formed by an anthropomorphic figure and a geometric motif (Figure 9).

Figure 9. Detail of one engraving block, lower part

This segmentation was first of all useful in calculating the width measurements of the individual blocks; in this way it was possible to understand how far the various portions differed from each other in terms of dimensions. Table 1 reports the width values of the blocks calculated from the unrolled mesh (lower part) and the arithmetic average of the width values. As can be seen from the table, block 4 of engravings presents the highest deviation from the mean value, i.e. 4.9 mm. This may suggest that the realization of the engravings on the receptacle was carried out with great precision and respect for the proportions between the dimensions of the individual blocks, to the millimetre level.

Engraving block n.	Width, mm	Average, mm
1	125,9	
2	123,8	
3	125,0	
4	120,9	
5	129,9	
6	127,6	
7	127,4	
		125,8

Table 1. Width measurements of the lower part engraving blocks and average value

Furthermore, the engraving blocks were imported in the free software *MeshLab* to perform surface enhancements aimed at emphasizing the engraving details. The *Minnaert* reflection model (Visual Computing Lab, 2006) was firstly applied as a shader.

This lightning model works by adding darkening limbs to the lighting equations to darken the surface in function of the viewing directions; it performs reflected light intensity adjustment depending on material’s curvature and characteristics, providing the reflected radiance of the object. Hence, rotating the model, the finest details of the engraved surface are emphasized by lights and shades (Figure 10).

The outcome is a detailed visualization of the 3D models representing the engraved blocks, which allows also to appreciate the finest materials detail of the basalt receptacle due a very high accuracy in the geometry reconstruction.

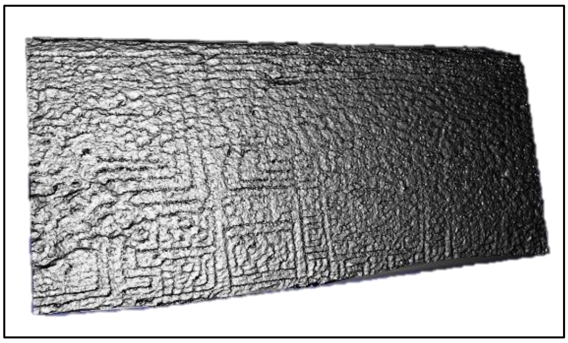

Figure 10. *Minnaert* shader applied to one engraving block

3.4 Vectors extraction from 3D model

Subsequently, the segmented "blocks" were used to extract scalable vector images of the represented figures. The employment of vector format instead of raster allows for zooming within the graphics while avoiding loss of resolution, as it is formed from vectors instead of pixels.

The vectorization from mesh procedure was carried out with *Blender* opensource software. The 3D meshes (.Obj) of the single engraving blocks were first imported in the 3D modeling software. Then, the 3D models were converted from mesh to “Curve” entities. After that, the resolution of the curve has been adjusted to increase the points forming the curve.

The output file was then set to “SVG” and the file was finally exported as a vector graphic in SVG (Scalable Vector Graphics) format, to be open in a browser or in a graphics software.

The lines depicting the engraved figures are represented but also some surface defects are visible in the graphics. This effect could be corrected with a manual selection of the points extracted from the mesh or editing the vector graphic in a dedicated software, to improve the general quality of the final product.

The final vector graphics, obtained for each of the engraving blocks, have been provided to archaeologists to be visually inspected and to allow them to compare graphic representations of the engravings made by hand and present in books and publications about Tiwanaku archaeology (Posnansky, 1958; Agüero et al., 2003; Torres 2004 & 2014).

4. CONCLUSIONS AND FUTURE PERSPECTIVES

The scanning methodologies and digital elaboration conducted for this research proved valuable for the purpose of documenting and investigating the Tiwanaku basaltic receptacle. The 3D model obtained presents a very high resolution (0.1 mm) that accurately reproduces the geometry of the object, while the texture calculated from camera-acquired images gave photographic realism to the model.

The unrolling operations conducted made it possible to visualize the engravings of the receptacle in sequence by projecting them onto a plane. This led to better visualization of the engraved figures. Moreover, the surface enhancement applied to the single engraving blocks, allowed for further inspection of the superficial morphology.

These digital operations have offered new possibilities for the study and analysis of the figures and the characteristics of the iconographic details. The lower and upper surfaces unrolling contributed to highlight proportion attributes, as well as evidencing the peculiarities of the representations of the solar deity and his attributes.

The resulting digital products can serve then as a tool for archaeologists and historians studying Tiwanaku and the artifacts found in the area, and can help them to better understand the traditions, society and religion of the civilization that inhabited these areas through the identification and interpretation of the iconography depicted on the basalt receptacle.

Furthermore, this research was conducted mainly with free and/or open source software, presenting a methodology that is quick and easy to replicate for other similar case studies, from archaeology or other fields. Nonetheless, the initial processing operations were performed with the scanner manufacturer's proprietary software. This choice was forced because the raw data acquired by the structured light projection scanner can only be processed with the software associated with the instrument. Moreover, the operation of geometric primitive fitting and related measurements extraction was also performed with the proprietary software. Nevertheless, the primitive fitting and all the subsequent operations can be performed in open source and/or free software.

As for the future perspectives arising from this research, other strategies for the geometry unrolling could be explored, involving software that can work directly with the solid mesh instead of point clouds. The mesh to point cloud conversion may decrease the initial accuracy in the geometry reconstruction, hence it is preferable to avoid this step. Furthermore, the point cloud was again converted in a solid mesh, exploring open-source software algorithm for surface reconstruction. The point cloud remeshing procedure could be in the future explored further to better evaluate the outcomes also considering other strategies.

Moreover, further work should be conducted to improve the quality of the vector graphics extracted from the 3D model. With better digital outcomes of this type it will be possible, for example, to use vector graphics extracted from the 3D model to perform a comparison between the graphics and the drawings made by hand by archaeologists over the past decades, superimposing them. In this way, it will be possible to investigate concerning the religious iconography reported in books and publications about Tiwanaku, drawing out conclusions about the significate of the engraved symbols.

In addition, other operations can be conducted from the digital products; it could be possible for example to insert the 3D model of the receptacle within its original context, then integrate the survey with the scan of the semi-subterranean temple of Tiwanaku and digitally reconstruct its original configuration. Geomatic surveys have been conducted within the archaeological site (Cothren et al., 2007), providing digital outcomes that could be integrated with the 3D products obtained by other institutions and academics. Moreover, virtual and/or augmented reality applications could be considered for navigating the archaeological 3D site model.

In conclusion, this research has demonstrated again how geomatic technologies, more specifically high-resolution 3D surveying and digital elaborations, can be a valuable tool and aid to the work of professionals involved in archaeological research.

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