3D PRINTING FOR DISSEMINATION OF MAYA ARCHITECTURAL HERITAGE: THE ACROPOLIS OF LA BLANCA (GUATEMALA)

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ABSTRACT:

This paper focuses on the use of 3D printing as a tool for the dissemination of Maya architectural heritage. The case study is the Acropolis of La Blanca, the main complex of this archaeological site located in the Peten department, Guatemala. One of the objectives of La Blanca Project was to create a model of the Acropolis as part of the strategy for dissemination and as a didactical resource for the Visitor Center. The documentation of this architectural complex with digital survey techniques allowed to obtain a high-fidelity model of the Acropolis' buildings. In order to achieve this goal, it was necessary to develop a methodology for the reverse modelling of the Acropolis, starting from the data obtained by laser scanning. We developed a workflow to create a virtual replica of the Acropolis optimized for 3D printing. This model was first printed in 17 parts by using the FDM technology. Then, it was transported to Guatemala and, finally, it was reassembled and placed at the Visitor Center. Today, this physical replica of the Acropolis is an important resource that allows the visitors to have a complete view of the main complex of the site, which is not easy in the Guatemalan jungle. It also provides an exclusive view of some parts of the Acropolis, already studied by researchers and now protected with a soil layer to ensure their preservation. Moreover, it is a useful resource for supporting dissemination and also serves as a teaching resource for student visitors.

1. INTRODUCTION

The Visitor Center of the archaeological site of La Blanca, in Guatemala, was built in 2010. This ancient Maya settlement stands out for the architecture of its Acropolis and has been studied since 2004 within the framework of La Blanca Project, led by Cristina Vidal Lorenzo (University of Valencia) and Gaspar Muñoz Cosme (Polytechnic University of Valencia). The Visitor Center is designed as a reception area where tourists receive support and locals participate in workshops and training programs related to cultural heritage (Muñoz et al., 2010). It also has an exhibition hall equipped with educational materials such as informative panels, plans and models that show the results of the research project and, at the same time, support the visit of the site. One of the objectives of La Blanca Project for the 2017 field season was to extend these resources by introducing of a scale replica of the Acropolis.

Before digital survey techniques were introduced to the study of historical buildings, the workflow used to obtain a scale replica of such buildings consisted in identifying the main geometries of the objects and reproducing them in a simplified way. Certainly, this simplification depended on the criteria adopted in the traditional survey's workflow, which involves the "discretization" of the building geometries to obtain an agile and correct representation through classical drawings such as plans, sections and elevations. The simplification process was also based on the scale of representation chosen, the technique adopted and the materials used to create the model. Thus, before digital survey techniques, it would have been very difficult to achieve an accurate representation of the Acropolis' architectural remains, considering its advanced state of decay. Over the past two decades, however, the development of the 3D survey techniques is increasingly changing the workflow in the documentation of cultural heritage (Guidi et al., 2010). The most important change has been the division between the data collection phase and the data processing phase. Due to this change, it is now possible to obtain very accurate 3D models of the objects surveyed by active sensors, based on laser scanning technology, and by passive sensors, based on digital photogrammetry technology. It is possible, moreover, to process these models in the laboratory to obtain both classical drawings and three-dimensional representations (Benedetti et al., 2010; Cipriani et al., 2014).

Nowadays, the use of these digital tools has been introduced in a considerable number of archaeological projects in the Maya area (Remondino et al., 2009; Tokovinine, Estrada-Belli, 2017). La Blanca Project has always been a pioneer in experimenting the application of these techniques to Maya archaeology and architecture (Vidal et al., 2017). In this paper, we report the results of using reverse modelling techniques to obtain a 3D printed replica of the Acropolis, testing its application to Maya architecture. The objectives of this work were:

- To create a model of the Acropolis as a means to improve the contents of the exhibition hall in the Visitor Center;
- To study in depth all the procedures used to obtain the Acropolis reality-based model and propose a workflow that could be used in similar cases;
- To test the use of this resource in the strategy for dissemination and as a didactical tool for the Visitor Center.

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2. THE ACROPOLIS OF LA BLANCA

La Blanca is a small Maya archaeological site located near the Salsipuedes River in the Peten department, in northern Guatemala. This river is part of the Mopan River's Valley, an area that became a strategic location for trade during the Late Classical Period (AD 600-850), when a large number of small settlements were established along its waterways. La Blanca developed quickly as an administrative and commercial city (Muñoz, Vidal, 2014) and the Acropolis was built as a residence for the city's rulers.

The settlement is structured along a north-south axis aligned about 12 degrees west of the geographical north. The main buildings and public spaces of the city are located along the two sides of the causeway, which corresponds to this axis (Figure 1). The residential area[1] is on the west side, while the Great North Square[2], the Acropolis, the Reservoir and the South Group[3] are located on the east side. The Acropolis is considered as the main architectural complex of the site, due to its impressive monumental dimensions (Vidal, Muñoz, 2016). The complex consists of three buildings located on a platform accessible from the North Square via a monumental stairway:

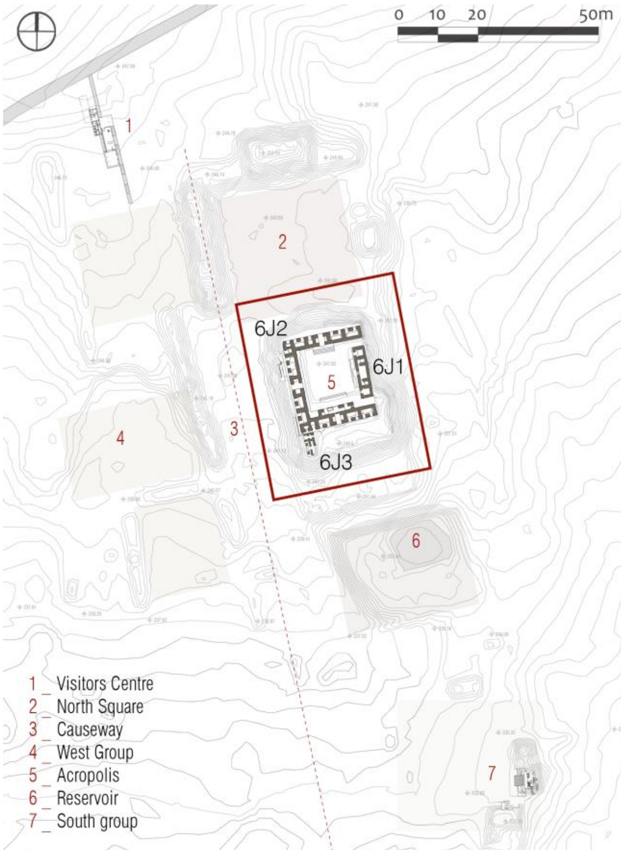

Figure 1. Plan of La Blanca with localization of the Acropolis.

- The 6J2 Palace is a U-shaped building with three wings forming an interior courtyard of approximately 36 m on each side;
- The 6J1 Palace, also known as the "Orient Palace", is located on the east of the platform closing the central courtyard;
- The 6J3 Palace was built as the ideal prolongation of the 6J2-west wing and it stands on the south terrace.

The 6J1 and 6J2 buildings are covered with a thatched-roofs system protecting almost all of the Acropolis' remains and ensuring their conservation (Figure 2). However, this thatched-roofs system provoked occlusions during the laser scanner data collection, especially in the highest areas of the walls, where it caused large shadow areas in the resulting point cloud. The 6J3 building is no longer visible today because it was protected with a soil layer, after the documentation with digital techniques, in order to ensure its preservation (Muñoz et al., 2015).

Figure 2. Southeast area of the Acropolis with its thatched-roofs system.

3. DIGITAL SURVEY OF THE ACROPOLIS

The documentation of the Acropolis by digital survey techniques started in 2012 with the introduction of a Faro Focus^{3D} S120 scanner into the project. This tool is a high-speed Terrestrial Laser Scanner (TLS) that offers efficient 3D measurements. It is also a very compact instrument, which makes it useful for operations in archaeological environments. The first goal was to experiment the use of these digital techniques for the documentation of the architecture in this particular archaeological context. The second goal was to obtain an accurate model of the Acropolis. The data collection was performed gradually in different field seasons, due to the difficult operating conditions of the site and according to the needs of the research project (Merlo et al., 2017). In total, three digital survey campaigns were conducted between 2012 and 2015 (Vidal, et al., 2017):

- The Orient Palace and the central courtyard were surveyed in 2012, with the acquisition of 36 point clouds;
- The 6J2 Building south wing and the first part of its west wing were recorded in 2013, with a total of 36 point clouds;
- The second part of the 6J2 west wing, the 6J2 north wing and the 6J3 Building were documented in 2015 with 46 point clouds.

As a result of these campaigns, a total of 118 scans were acquired, each of which had a resolution ¼ (1 point for each 4 mm up to 10 m away) and an accuracy 4x (the measurement of

[1] It consists of a series of minor public squares delimited by mounds.
[2] The North Square could host almost 20,000 people during the ritual celebrations of the city (Muñoz Cosme, Vidal Lorenzo, 2014).
[3] The South Group is the religious complex of the city. It consists of three temples located around a small square.

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each point is the average of 4 reiterations). Having acquired these scans, we carried out the point clouds registration in a laboratory and obtained the reality-based Point Cloud Model of the Acropolis (Table 1). This model showed a very high geometric accuracy and was useful for extracting 2D classic drawings and for obtaining 3D polygonal mesh models.

Point Cloud Acquisition Parameters	
Laser Scanner	Faro Focus^{3D} S120
Resolution	1/4
Quality	4x
Average Distance Scanner-Object	5 m
Number of Scans	118
Acquisition of Photos	No
Resultant Point Cloud Model	
Number of Points	3,790 x 10^6 pt
Registration Accuracy	3 mm
Database File Size	85 Gbyte

Table 1. Acquisition Parameters and final Point Cloud Model.

4. REVERSE MODELLING OF THE ACROPOLIS

4.1 Reserve Modelling for 3D Printing

A 3D printer allows to obtain a physical scale replica of a 3D model that has been previously produced by a computer. In general, it is possible to print 3D objects starting from a traditional 3D model that has been modelled directly (as in the case of the model of a building we are designing) or from a reality-based 3D model that has been obtained from real data acquired by laser scanning or by digital photogrammetry (Verdiani, Gira, 2015; Meschini, Sicuranza, 2016).

The existing types of commercial 3D printers differ not only in their technology and impression mode, but also in the typology of materials used and in their physical-chemical features. In this study, we used an FDM[4] printer, which melts the PLA[5] plastic material, extrudes it, and progressively deposits it layer by layer on the printing desk. The 3D model is virtually sectioned and then physically built in thin layers (Verdiani et al., 2016). A 3D model useful for 3D printing must satisfy two specific requirements:

- The Mesh must be waterproof, without boundaries in its structure. Otherwise, the printer cannot work properly;

- The number of polygons of the mesh must be limited to simplify the print management by the 3D printer software and hardware.

4.2 Construction of the Polygonal 3D Model

Reverse modelling software have tools for creating a 3D polygonal mesh from a Point Cloud Model. These procedures allow to automatically obtain a mesh by triangulating the points of a discontinuous model (Guidi, 2014).

4 Fused Deposition Modelling.

5 Poly Lactic Acid, a biodegradable polymer.

However, it is usually necessary to optimize the first mesh in order to obtain a high-quality model suitable for 3D printing. Reverse modelling software have also automatic and semi-automatic tools to run mesh optimizations. The construction and the optimization of the Acropolis' 3D mesh model was a difficult operation for two reasons:

- Redundancy of data acquired in three different survey campaigns, from 2012 to 2015 field seasons;

- Lack of data in the highest parts of the wall. As mentioned before, the thatched-roofs system caused occlusion areas.

For constructing and optimizing the Acropolis' mesh model, we followed the following procedure. First, the 3D point model of the Acropolis was exported into *.ptx* format in 9 parts. Then, every section of the model was imported into the software *3D System Rapidform* with a ¼ factor of reduction. In the same software, we built separately 9 different high-poly meshes. The sum of all these meshes would have produced a model of 43,840,184 polygons (Table 2). It would have been as accurate as difficult to manage with the available hardware and software.

High-Poly Mesh Data	**Polygons' Number**	***.xrl* File Size**
6J1 Palace	3,427,009	190 MB
6J2 Palace – north wing – part 1	2,102,592	104 MB
6J2 Palace – north wing – part 2	4,162,670	203 MB
6J2 Palace – west wing – part 1	5,273,949	260 MB
6J2 Palace – west wing – part 1	6,572,329	321 MB
6J2 Palace – south wing – part 1	6,092,059	296 MB
6J2 Palace – south wing – part 1	8,336,296	406 MB
6J3 Palace	3,971,981	196 MB
Central Courtyard	3,902,299	188 MB
Entire High-poly Mesh Model	**43,840,184**	**2,424MB**

Table 2. High-poly model of the Acropolis, data.

The heterogeneous structure of the single 9 meshes was an additional problem caused by the higher or lower redundancy of data acquired in different field seasons. Therefore, we decided to practice a *global re-meshing*[6] of all the 9 meshes with three objectives:

- Reduce the polygons' number of the final model;

- Homogenize the average size of the polygons' edges;

- Homogenize the number and the distribution of the polygons on the final model.

Once the global re-meshing operations had been performed, we processed each mesh separately in order to eliminate topological errors[7] and to fill their boundaries. Finally, we combined all the meshes and obtained a medium-poly model of the Acropolis, which consisted of a 5,569,347 polygons mesh with a homogeneous structure (Table 3).

6 Automatic procedure used to improve the quality of a mesh by re-triangulating the polygons.

7 Such as overlaying polygons, redundant polygons, crossing polygons, etc.

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Final Mesh Data	**Polygons' number**	***.xrl* File Size**
6J1 Palace	805,361	39 MB
6J2 Palace – north wing – part 1	526,610	25 MB
6J2 Palace – north wing – part 2	572,600	28 MB
6J2 Palace – west wing – part 1	857,268	42 MB
6J2 Palace – west wing – part 2	748,659	36 MB
6J2 Palace – south wing – part 1	668,273	32 MB
6J2 Palace – south wing – part 2	684,158	33 MB
6J3 Palace	443,783	22 MB
Central Courtyard	976,290	46 MB
Final Mesh Model	**5,569,347**	**278 MB**

Table 3. Reality-based mesh of the Acropolis, data.

4.3 Integration of the 3D Model: a Method

It was still necessary to integrate, in the undetected areas, the 3D model we had obtained with the procedures described above (Figure 3). We decided to study the use of the reverse modelling techniques and the application of other methods that are commonly used for game engines and computer graphics, trying to merge the use of specific tools from each software, in order to complete our model[8].

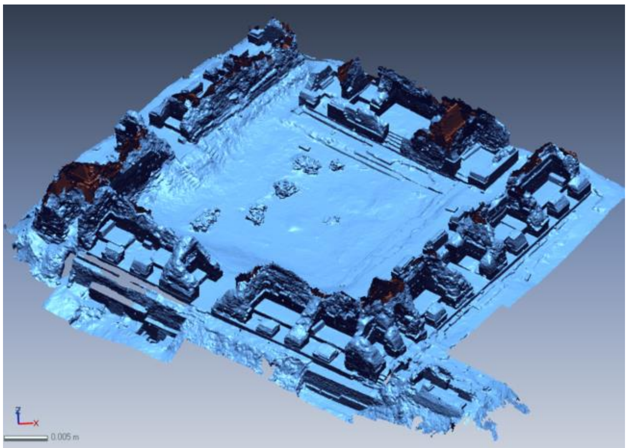

Figure 3. Reality-based mesh of the Acropolis.

First, we did a manual retopology[9] of all the boundaries of the model by employing *Luxology Modo* (Figure 4a), with which we obtained several simplified contours. Second, these contours were used as references for the direct modelling of the missing sections of the Acropolis (Figure 4b). This new mesh was a simplified and quadrangular polygons-based representation of the Acropolis' undetected geometries. As a result, it was not homogeneous with the rest of the model and it was still unable for the integration (Figure 4c). Last, it was necessary to homogenize the structure of the two meshes. This operation was conducted in three steps. First, the geometries of the reconstructed mesh were relaxed by using the smoothing tools of *Luxology Modo*. Then, it was optimized by running a global re-meshing in *3D System Rapidform* (Figure 4d), this time, with the aim to increase the number of polygons and to obtain a structure similar to that of the Acropolis' mesh.

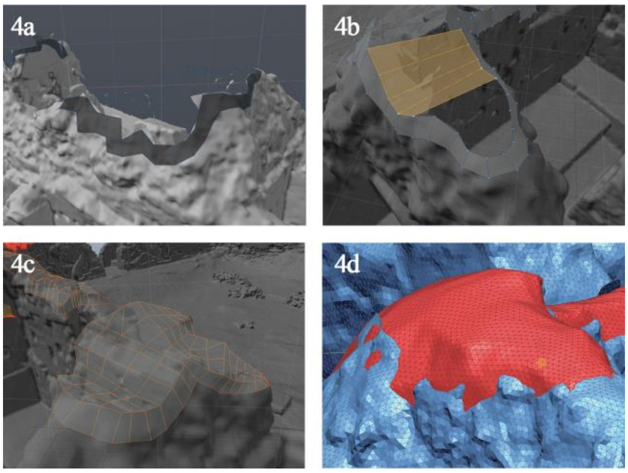

Figure 4. Integration of the model (4a: Retopology of the boundaries; 4b: Direct modelling; 4c: Resultant mesh; 4d: Smoothing of the mesh).

Next, the two meshes were merged into a single model. Even though the integrated parts presented a structure very similar to the reality-based one, they still had excessively simplified geometries (Figure 5).

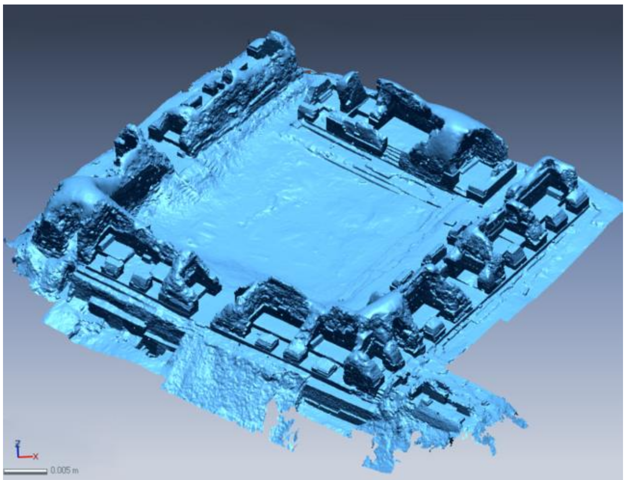

Figure 5. Reality-based mesh of the Acropolis integrated in the undetected areas.

We then decided to improve the homogenization of the model by using the sculpting[10] tools of the software *Maxon Cinema 4D*. The use of this technique helped increase the geometrical complexity of the reconstructed parts of the model. It also helped emphasize the difference between the reality-based parts of the model and the directly modelled surfaces that had been undetected by the laser scanner (Figure 6).

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[8] All the export-import operations were obtained through the *.obj* format, an universal exchange format supporting mesh models between 3D software.

[9] This technique is usually employed to build simplified 3D models formed by quadrangular polygons, starting from complex high-poly meshes.

[10] Sculpting is a popular technique of three dimensional modelling developed for video games and animation environments. It consists of manipulating digital objects by sculpting them as objects in the real world.

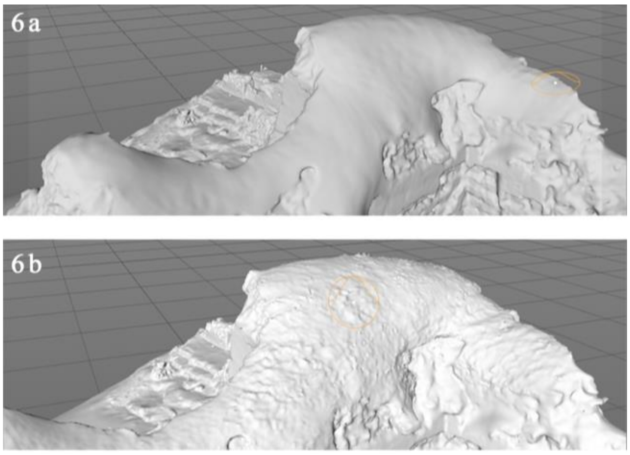

Figure 6. Homogenization of the model (6a: model integrated in the undetected areas; 6b: mesh after the sculpting application).

The 3D model of the Acropolis was finally completed by integrating the terrain mesh. In this case, we opted for a geometric modelling tool that supports the subdivision surfaces, which can be easily used trough a low-poly control cage. The model of the mound was then merged into the Acropolis once again using *3D System Rapidform*. The resulting model was a waterproof 3D model of the Acropolis, consisting of 6,043,072 polygons with a homogeneous structure over the entire mesh, ready for 3D printing (Figure 7).

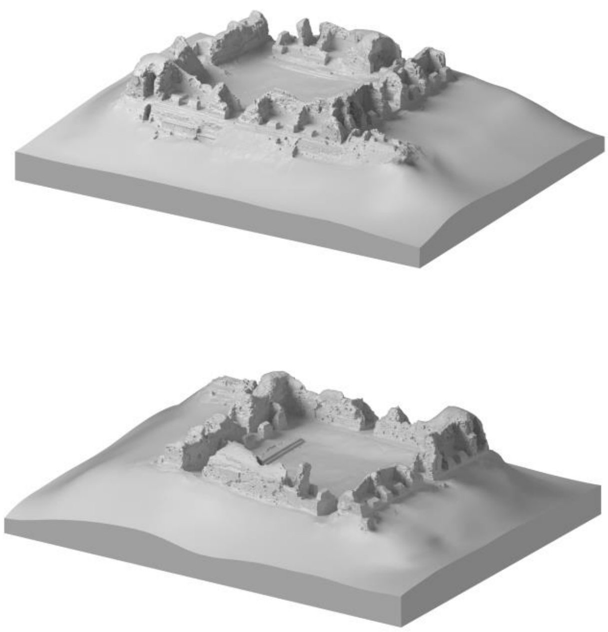

Figure 7. Views of the final model of the Acropolis.

4.4 Accuracy of the Model and some Observations

Before proceeding with the 3D printing, we decided to compare the final model with the original high-poly meshes, in order to evaluate the errors introduced in the optimization phase. Figure 8 shows the mesh deviation between the final model and one of the high-poly meshes. The color scheme[11] shows the areas where the overlapping has a higher similarity between the two meshes in green and the areas where this similarity is lower in red. The resulting average mesh deviation was included between +0.25 mm and -0.25 mm in almost the entire model, excluding, of course, the parts that were manually modelled.

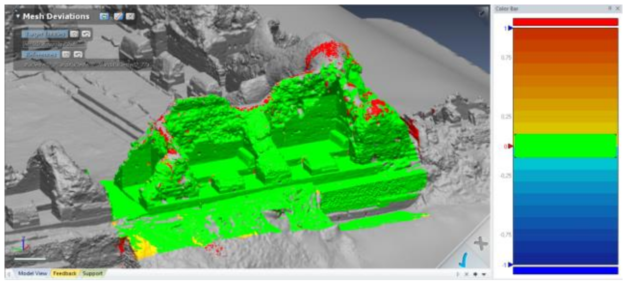

Figure 8. Mesh deviation between the final model and a section of the high-poly model.

If we compare this deviation with the maximum accuracy of 0.1 mm[12] that our FDM Printer can achieve and considering that 0.1 mm in 1:100 scale would give an inaccuracy of 1 cm in the real world scale, we can affirm that the optimization procedures described in this paper introduced an irrelevant error for our objective.

5. THE 3D PRINTED MODEL OF THE ACROPOLIS

5.1 Print Tests

Before printing the entire model, we decided to run some print tests with different scales and precision configurations to compare their quality and choose the correct settings. We used the *.stl*[13] file format to transfer the three-dimensional data to the 3D printing software[14]. Four sections of the Acropolis model were printed in PLA with the FDM technology. A list with the descriptions of the four proof models is illustrated below (Figure 9):

- Southwest corner of the 6J2 Palace (section of rooms 5 and 6) in scale 1:250 and accuracy 0.1 mm (Figure 9a);
- Southwest corner of the Acropolis (section of rooms 5 and 6) in scale 1:200 and accuracy[15] 0.1 mm (Figure 9b);
- Southwest corner of the Acropolis (rooms 8, 7, 6, 5) in scale 1:200 and accuracy 0.2 mm (Figure 9c);
- West wing of the 6J2 Palace and 6J3 palace in scale 1:250 and accuracy 0.2 mm (Figure 9d).

[11] In a color range which goes from green to red in case of positive deviation and from green to blue in case of negative deviation.

[12] This value is given by the minimum height of the layer that the 3D Printer can obtain.

[13] *.stl* is the abbreviation of "stereolithography". This file format is supported by many software packages. It is widely used for 3D printing and rapid prototyping.

[14] For all 3D Printing operations, we had the support of Bemore3D, a start-up founded at the Polytechnic University of Valencia, which is specialized in 3D printing with different technologies and materials.

[15] Determined, as mentioned before, by the height of the levels.

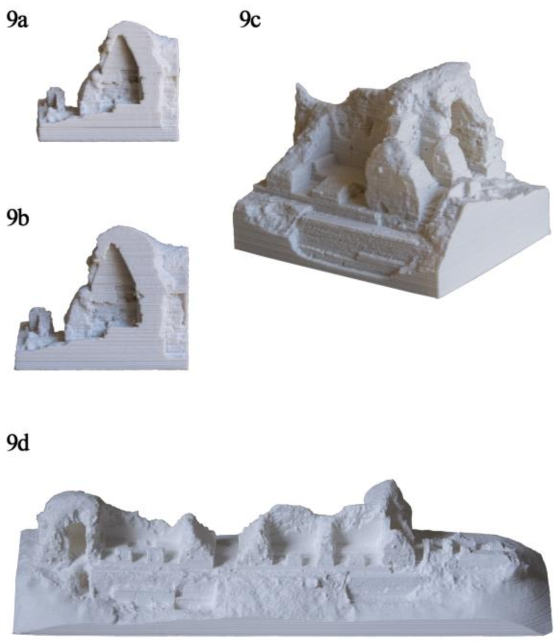

Figure 9. Print tests (9a: scale 1:250 and accuracy 0.1 mm; 9b: scale 1:200 and accuracy 0.1 mm; 9c: scale 1:200 and accuracy 0.2 mm; 9d: scale 1:250 and accuracy 0.2 mm).

Figure 10. Print tests in scale 1:100 and accuracy 0.3 mm.

The four print tests presented all a very high accuracy when compared with the virtual model. The morphological and geometrical features of the reality-based parts of the model appeared to be successfully achieved in each printed version. The missing parts of the Acropolis, undetected by laser scanner and then manually reconstructed, appeared to be perfectly integrated in the 3D printed version of the model and showed, at the same time, their diversity from the reality-based parts of the model.

From the analysis of these tests, we concluded that the representation of the Acropolis was satisfactory. Nevertheless, we decided to perform another test in scale 1:100 in order to compare the quality of the model at this scale larger than the previous ones, as well as to evaluate the possibility of obtaining a replica of the Acropolis as large as possible with the available tools. Therefore, our final test was:

- Southwest corner of the 6J2 Palace (rooms 5, 6, 8 and 9) in scale 1:100 and accuracy 0.3 mm (Figure 10).

As this last test resulted once again largely satisfactory, we concluded that the final 3D printed version of the entire Acropolis had fully accomplished our objectives in each of the scales and accuracies tested.

5.2 The Replica of the Acropolis and its Installation in La Blanca: a Resource for the Visitor Center.

Considering that the 1:100 test showed a high fidelity with the virtual model of the Acropolis, we opted to print the entire model in this scale with an accuracy of 0.3 mm. As the measurements of our model were 90 m long by 70 m wide, the printed replica would measure 90 cm by 70 cm at the chosen scale. The 3D printer we used works on a printing desk measuring 32 cm by 25 cm, so it was necessary to cut the Acropolis' model into parts and print each one separately (Figure 11).

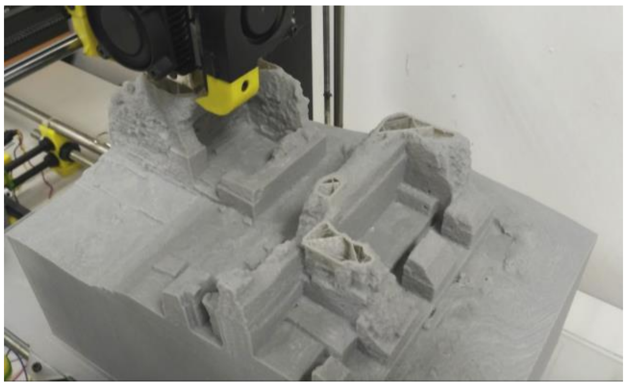

Figure 11. 3D printing of a part of the model in PLA material by FDM Printer.

Thus, we obtained 17 printed parts of the Acropolis in scale 1:100. This sectioning was very useful to facilitate the transport of the model to La Blanca, in Guatemala. Finally, the Acropolis was reassembled *in loco* during the 2017 field season (Figure 12).

Figure 12. Final 3D printed model of the Acropolis consisting of 17 parts reassembled in La Blanca.

The Acropolis model was placed in the center of the exhibition hall in La Blanca's Visitor Center. Our staff prepared a masonry base and faced it with a wood panelling. This base served as a support for the model that was finally protected with a transparent plastic dome (Figure 13).

In this way, we obtained a physical scale replica of the Acropolis, which improves the contents of the exhibition hall in the Visitor Center. Today, it is used as a dissemination resource for visitors, who can obtain information about La Blanca and the Research Project. Visitors can find the correspondences between the images showed in the panels and the printed model, as well as enjoy an overview of the current state of the Acropolis and observe the 6J3 Palace in context.

The model is also used as a teaching resource for local schools that often bring children to the site in order to carry out field practices on the history of Maya civilization. Moreover, it is a useful tool to sensitize and educate young generations on the conservation and appreciation of their cultural heritage.

Figure 13. The Acropolis replica in the Visitor Center of La Blanca.

6. CONCLUSIONS

3D printing is a very valuable resource for improving dissemination practices, especially for expanding the contents of museums and interpretation centres. The possibility of obtaining very accurate physical replicas of archaeological remains is highly helpful for researchers, students and visitors, especially in the case of Maya architecture, which is often hidden under the dense tropical rainforest of Central America.

In La Blanca, we obtained a physical scale replica of the Acropolis, which permits to enjoy an overall view of the architectural complex. This is not possible when visiting the site because of both the vegetation and the thatched-rooftops system that protects the Acropolis.

Architecture is the expression of the economic, political and social circumstances in every specific historical moment of any civilization. Thus, an overall view of the historical buildings can be helpful for understanding their geometries, proportions and formal characteristics. The La Blanca 3D printed model is also extremely useful for showing architectural remains that have already been excavated, studied, covered for their preservation, and that are no longer visible, as in the case of the 6J3 Palace.

The reverse modelling method we have presented in this paper and used for the construction of a reality-based model and for the integration of the undetected parts ensured a very high accuracy level in the 3D printed model. The quality of the representation was highly satisfactory and adequate for dissemination activities related with La Blanca Project. We find that this method can also be applicable to similar cases.

Our next goal concerns modelling a virtual reconstruction of the Acropolis, starting from the reality-based model. This work will help us continue our research on Maya architecture by formulating hypotheses on the original volumes of the Acropolis. The final 3D restored version of the Acropolis will be printed in scale and then positioned close the previous one in the Visitor Center of La Blanca. This new action for dissemination will improve the contents of the Visitor Center, offering to the visitors a comparative view of the current state of the Acropolis along with a hypothetical configuration in the period of maximum splendour. The Polytechnic University of Valencia, through their funding for the project "Fortalecimiento Comunitario para el Desarrollo Sostenible de la Blanca, Guatemala" (AD1915), has already supported this work.

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