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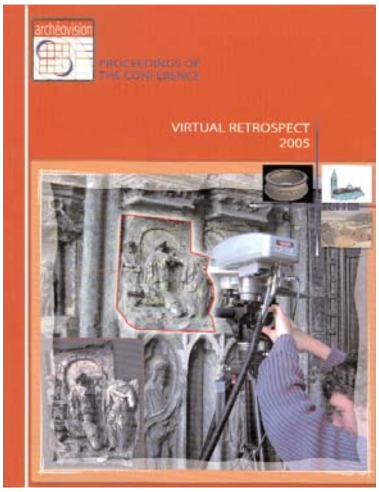

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Abstract : To construct virtual models of the pre-Hispanic archaeological sites of Bonampak, Cacaxtla and Suchilquitongo for their exploration in real time in the immersive virtual reality system of the National University of Mexico (UNAM), we used different methodologies and obtained results with different levels of precision. The relation between these characteristics and their potential for research, teaching and documentation of historical architecture is explained. The three sites have a good amount of mural painting which make them particularly interesting for several disciplines such as history of art, conservation, and archaeology. Nevertheless, each use has specific requirements that the 3 models cover in different ways.

Keywords : Virtual Reality — Archaeology — Cultural Heritage — Documentation — Digital Preservation.

1 Constructing the models

We applied different methods to transport the 3 sites to a virtual reality environment, depending on the objective of the work, the characteristics of the site, the material resources and available time. In the 3 cases we made an in situ survey of the structures, which served to analyse each site and to construct the models. However, for reasons that we shall explain below, while Suchilquitongo presents a high degree of precision, Bonampak is simplified and Cacaxtla is “idealized”.

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1.1 Bonampak

Bonampak is a Mayan site in southern Mexico, near the border with Guatemala; its age of splendor corresponds with the accession of the king Chaan Muan II, in 776 A.D.[1], date registered in paintings and stelae. Mayan civilization gave much importance to the recording of time, and since 550 B.C. it based its calculations on the solar year. Bonampak is far from any urban center, isolated in the rain forest, which makes access difficult. It is a rather small site which is appealing because of the amount and quality of mural paintings that cover the walls and vault of three rooms in one of the structures. The humid, tropical climate and exuberant vegetation have affected the buildings and very few paintings have survived these aggressive environmental conditions. Most of the painted stuccoes that originally covered facades and interiors have fallen or were covered in fungi. But, here, the formation of a crystalline layer of salts protected the paintings. The difficult access, the importance and fragility of the mural paintings, are all factors that underline the importance of counting on a digital representation of the site.

The aim of this model, made in 2003, was multiple: we were looking for a monument with strong visual attraction to demonstrate, in a spectacular way, how virtual reality can be used in teaching and for research on archaeology, pre-Hispanic mural painting, and Mesoamerican culture. This site, because of the beauty of its natural surroundings and its pictorial representations, fulfilled this objective; it was the first model to use the virtual reality facilities of the University. We only had three months for the project and Bonampak was chosen because it was feasible to build the model in this reduced time-frame, thanks to the size of the site and to research on its mural paintings made by the *Instituto de Investigaciones Estéticas*. Several books had been published on Bonampak [2] and a reproduction of each one of the murals had been made in 1996 [3]; these files were made available to us.

Because of the characteristics of Bonampak, our objective was to show the integration of the mural paintings in their architectonic and environmental context. If the model required a correct description of the site, it did not demand a very high degree of precision: an error of ± 5% was acceptable.

The survey was done with a total station (Leica, TCR 703) during a 4-day trip with 4 people to the forest, and completed with digital photographs. The purpose of the latter was threefold: to conserve the visual records of the present state of the site, to extract the textures which were then applied to the polygons, and to use photogrammetry techniques (1) to obtain

Distance to the observer	Bonampak	Cacaxtla	Suchilquitongo
	Texture		
Painting, 0 - 3 m	1mm - 1.44px	1mm - 2.4px	1mm - 3px
Painting, more than 3 m	100mm - 1px	100mm - 1px	1mm - 3px
Exterior finishes	100mm - 1px	100mm - 1px	30mm - 1px
	Geometry		
Hollow wall, 0 - 10m	Complete geometry		
Hollow wall, more than10m	Simplified geometry		

Table 1: Level of detail.

the size of secondary elements that we did not have time to measure, such as structures located in the higher parts of the site which were modeled in simplified way, for example rooms without access.

The model geometry was built based on the data from the survey and photogrammetric information (2). The taluses were simplified, the ruins were smoothed and the different structures were defined without previous analytical work. In fact, what we currently observe, corresponds to several intermingled constructive stages in which taluses of previous stages, covered by other taluses, reappear between ruins. If there had been a previous analytical phase, the model would have been different, reflecting and incorporating an understanding of the logic of the visible elements.

We worked the model optimization so that real-time navigation with stereoscopy would be feasible. For example, in order to save texture memory space (raster manager in the Silicon Graphics computer), mosaic techniques were used for textures that might be repetitive, like the grass and stones of the taluses. The textures have different resolutions and different levels of detail, for example, the textures of walls, taluses, trees, and grass are applied with low resolution (table 1). The mural paintings have a resolution of 1.44 pixels per millimeter; nevertheless, the process to assemble them in 1996 was based on major image processing and several pixel interpolations, thus the result was not nearly as clear as normally expected with this resolution. The stelae and bas-reliefs of the thresholds were worked with lower resolution, 0.45 pixels per milimeter and without interpolations, yielding greater quality and clearness. The depths of the bas-reliefs were heightened with Photoshop. To obtain the required conditions to study the paintings, at the request of the historians, the interiors were worked without shading, with uniform lighting.

Geometries and textures were integrated within a scene graph – from the Creator program – which allows the definition of levels of details for textures and geometries, the control of collisions, and the organization of files to later optimize the computing resources for real-time navigation. For example, the trees are photographs stuck on polygons that are defined as "billboards," and turn towards the camera, always showing their better face.

Fig. 1: Bonampak, current state and virtual model.

1.2 Suchilquitongo

Located in the Mixteca Oaxaqueña, 6 hours from Mexico City, this is a tomb from Zapotec culture, which dates from 700-900 A.D.[4]. In its interior the decoration is impressive: walls are covered by mural paintings, doors and alcoves are surrounded by bas-reliefs, the upper part of the entrance and the door between the antechamber and the main chamber show high-reliefs, masks and a complete architectural entablature with friezes, cornices and moldings.

Since the beginning of the project, due to the reduced size of the tomb, we decided that the representation of each of the components had to have a very high level of detail and precision, in order to build up archaeological documentation

that would allow us to demonstrate how, in this case, the three-dimensional model becomes a highly reliable tool for conservation and research, and for studies that go beyond solely pure visual appreciation and perception. The Suchilquitongo model had to be a faithful copy of the tomb, exact in the representation of its paintings, colors and in the dimensions of each one of its components, and for that reason the survey was carefully supervised.
The field work began towards the end of 2004. All the measurements were taken with a total station, including walls, entablatures, and high-reliefs. Each painted wall was registered with multiple images to obtain a resolution of 4 pixels per millimeter of painting; each photograph was corrected by inverting the distortion resulting from the lack of parallelism between the wall and the camera, and the optical distortion of the lens; color was controlled using techniques based on the Macbeth card; the lack of uniformity in the lighting was also inverted. The corrected images were assembled using only one file per mural.
The structures of the tomb were modeled with a minimum of simplification vis-à-vis the main deformations of the walls. Bas-reliefs were represented as flat textures.
The model can be visualized in two ways, with uniform lighting, to study paintings without visual distractions or changes in color due to differences in lighting, or in light and shadow, which allows for a better appreciation of the effects of depth and the reliefs. Most likely, this lighting does not correspond to what originally existed, since the system used by the pre-Hispanic visitors of the tomb is unknown.

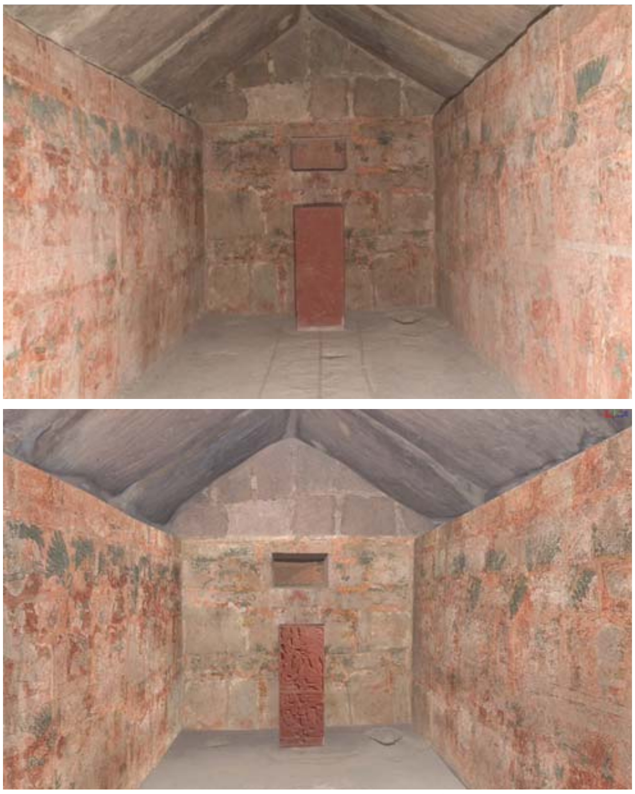
Fig. 2: Suchilquitongo, current state and virtual model.

1.3 Cacaxtla, hypothetical reconstruction
For Cacaxtla, located 2 hours from Mexico city, the approach was totally different from the previous cases, though the site is also known by the number and quality of its mural paintings, and it currently displays many intermingled constructive stages. We began to work in Cacaxtla at the beginning of the 1990s, initially to demonstrate how CAD systems could be used to obtain a complete recording of the 3D state of the ruins [5], and we built the model from existing drawings. Years later, work began with hypothetical reconstructions of the site and a survey was made with tape measurements. Based on the survey of its structures and finishes, detailed studies were made to trace the development of the site. We were able to identify several stages of construction and thus some of building techniques used by the architects of Cacaxtla; as a result, we were able to reconstruct it in several historical stages. For some of these stages, we obtained a complete configuration of the site, with different degrees of reliability in the reconstruction, whereas for others, the lack of data, due to the destruction of the structures or because they were still buried in lower levels, made a reconstruction with the same degree of certainly impossible.
The model is an "idealization" of the site, in the sense that geometries do not follow the structural deformations of the

Area	***Bonampak***	***Cacaxtla***	***Suchilquitongo***
Model	17207 m^2	18474 m^2	22 m^2
Mural paintings	150 m^2	172 m^2	30 m^2
Buildings	42.00%	49.00 %	100.00%

Table 2: Area covered by the models, mural paintings, and buildings.

	Bonampak	***Cacaxtla***	***Suchilquitongo***
Number of polygons	3451	13545	2045
Number of images	612	2958	745
Texture storage (in KB)	407175	1851294	574096
Polygons storage (in KB)	1573	5196	961

Table 3: Number and size of polygons and textures.

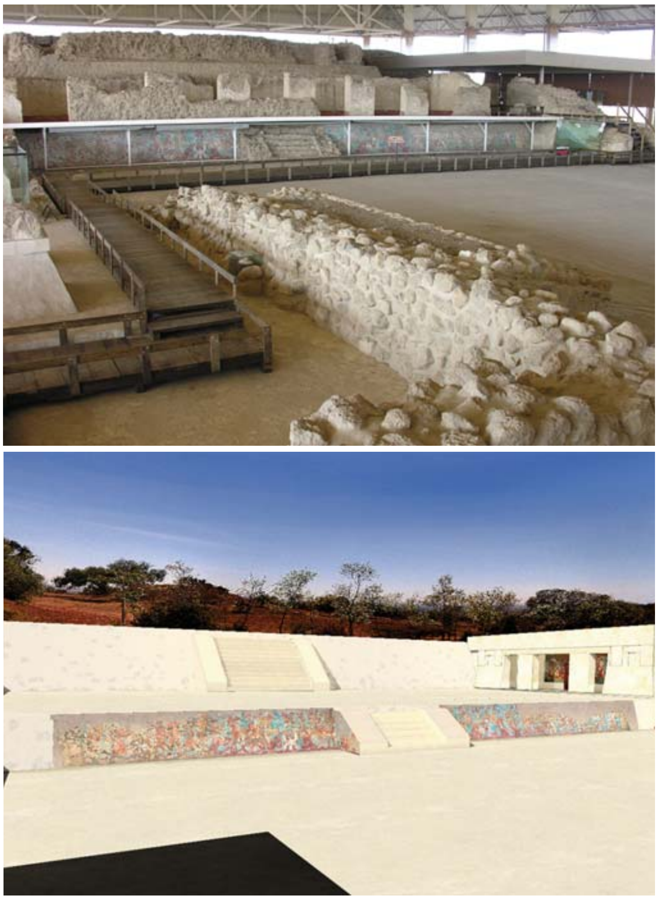

Fig. 3: Cacaxtla, current state and virtual model.

ruins [6] and that some of the construction principles we inferred were extrapolated to present and display original states, under the assumption that these rules were always systematically applied.

The tools used were the same as those used in both previous cases, but the method applied to obtain the textures of the materials were vastly different. In Cacaxtla, they were calculated with renders and later applied to the model. Particular care was taken for the lighting used in this calculation, using techniques that simulate the physical phenomenon of lighting with natural light. The materials are uneven, with irregularities, stains, cracks, etc., that make them seem more realistic.

2 Constructing the models

2.1 Models

As it can be observed in tables 2 and 3, Suchilquitongo is much smaller than the other two sites; in addition, its surface is more limited since it is a closed space. In Bonampak and Cacaxtla, the models were extended in order to integrate the landscapes. This difference in size is not directly reflected in the size of the texture files, as they handle different resolutions (table 3). What particularly influences the storage size are the requirements of the textures that cannot be handled like mosaics, as in is the case of mural paintings and the finishes obtained from renders.

One of the problems for navigation in real time is the size of the textures, which led us to work with representations of paintings with less resolution than the original digital file. As mentioned below, this problem is also solved by handling different levels of detail for textures and for geometries; however, this is not always possible when the aim of the 3D model is to have a tool to study mural paintings (table 1).

Due to the high demand for graphic resources required by each of the virtual models in the stereoscopic immersive system, a strategy was developed to efficiently optimize the images and geometries, so as to not lose fluidity in navigation.

From the outset, we decided that the mural paintings and bas-reliefs needed to have the highest possible quality to be able to appreciate details on zooming. Lesser importance was given to the exterior finish of the buildings and to other structures, like platforms, plazas, and the natural environment.

	Bonampak	***Cacaxtla***	***Suchilquitongo***
Data acquisition for the modeling	Total station and photogrammetry	Manual	Total station
Color of the materials	Subjective approximation	Subjective approximation	Spectrophotometer
Texture of the materials	Photographs	Renders with procedural and mapped textures	Photographs and spectrum works
Painting register	Subjective approximation	Subjective approximation	Control of distortion, color and lighting
Lighting	Photographs with manual compensation	Lighting simulation with radiosity	Homogeneous and light mapping obtained with radiosity
Natural environment	Billboards and screen for the landscape	Screen for the landscape	--

Table 4: Techniques used.

Although this information is important to perceive the space logic of the whole and for the walk-through as it provides references, scale, visual congruency, and distance it does not require as much precision as the iconographic representations. This led us to handle a pixel/metric units ratio in different proportions (table 4), and to apply different levels of detail. With this method, the quality of the images or geometry is less when the observer is far away, and as he or she approaches, the system upgrades the information to a higher quality.
The different levels of detail were applied with a scale in relation to the dimensions of the site; in the case of Suchilquitongo the reduced space of the rooms implies scant movement of the observers and so levels of detail are not defined.

2.2 Methodology used
Table 4 is a summary of the different techniques used to make the three models, and it shows the relationship between method of acquiring the information, the method of processing it, and the degree of precision obtained.

3 The University's virtual reality installations
These three models are used in the Visualization Observatory, *Ixtli* (3), a small auditorium for 40 people, built on the University campus to integrate virtual reality techniques into the academic activities of teaching and research. The image is calculated with an SGI equipment Onyx 3500, 12 processors, 24 GB RAM, and is projected in active stereoscopy to a 140 degree curved screen, 9 m long and 2.80 m high (fig. 4).
To interact with the models, in addition to the keyboard, there are sensors that allow interaction with movements of the head and hands.
The immersion in the image is very high due to the stereoscopy, the size of the screen, and its shape. Additionally, the room is completely dark and the only visible element is the projected image, which isolates the spectators from their real space and makes them concentrate on the digital image and the three-dimensional surrounding sound.
The room is also equipped with an Internet2 connection to integrate the virtual reality with a high technology communication system, thus generating a very interesting collaborative space. The first experiment was made with the University of California in Los Angeles, where there is an installation similar to the one at UNAM. In both campuses, we were able to see the same image of the three-dimensional model and to interact with it, and the videoconferencing system allowed us to see and speak to each other. Using virtual reality, two remote groups of researchers can study the same model, or a university professor can teach a course or give a conference at a distance.

4 Applications of the three models
When the three models are used in the virtual reality installation, there are differences in the potential uses of each one.

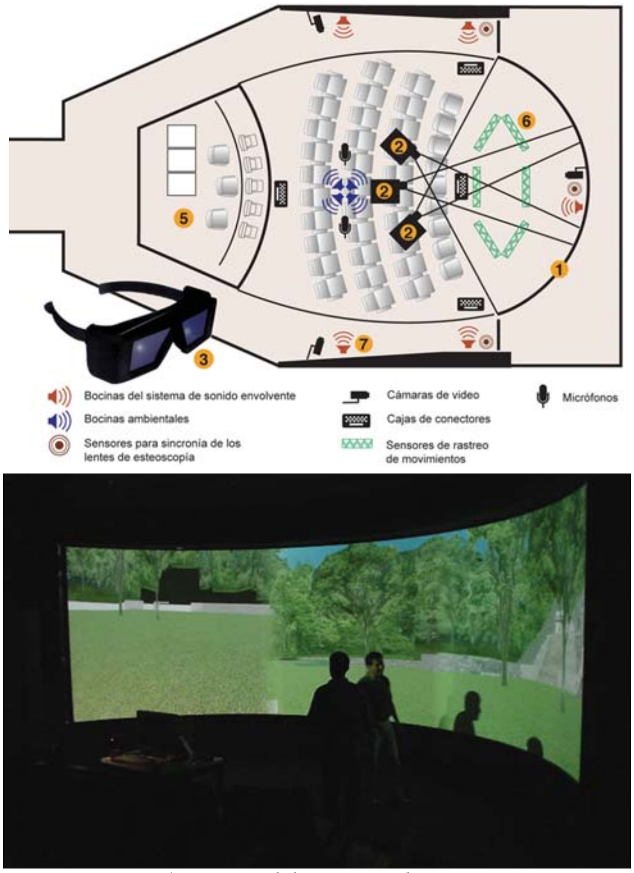

Fig. 4: Layout of the room and interior view.

All have the same features and limitations regarding the ease of navigation and the degree of immersion. With this tool, a teacher can explain the details of the paintings, how they are integrated into their architectural context, the space relation between iconography and building structure. The teacher can also make students see themselves in spaces that have very different characteristics, feel the closed space of a tomb, the dense green environment of the tropical forest before entering into the painted rooms of Bonampak. They can see that Cacaxtla, located on the top of a hill, has a view towards a very open barren space, with the Popocatepetl volcano in the background. Thus, there is a spatial experience that complements the rational part of a didactic explanation. In this sense, the pedagogical impact of virtual reality to explain archaeology has several aspects that go beyond being able to explain better and understand better as a result of seeing better. Virtual reality provides an emotional and sensorial experience that affects aspects related to feelings and existential memory. We mustn't forget that architecture is an art that not only solves the basic functional requirements or structural problems of a given building, it also reflects a series of social relations and relations with the environment; it sets the scale for different elements, a hierarchy that reflects mental hierarchies. Furthermore, architecture is a mean by which humans create a scene for their lives. Virtual reality facilitates this approach to architecture. There are other factors that contribute to the educational process, since students are more attentive in class, and the visual and emotional experience favors learning. An important variation in the use of the models results from the great differences in the degrees of precision among them. If we compare Bonampak to Suchilquitongo, the iconography of the paintings can be studied in both but in the latter we have a precise testimony of the tomb, an exact reproduction which conserves all the information with a high level of precision. Thus, a conservator can study the deterioration, the techniques used in restoration or use the model as a basis to evaluate the deterioration process. The hi-res with which the textures were registered lets us observe and study the paintings with a "zoom in," under better conditions than in the site itself. Additionally, fidelity to the model opens possibilities for research in history of art and architecture, to analyze brush strokes, visual balance, proportions, false perspective, the handling of depth with colors, etc. Because it is an exact document, the model is reliable for more demanding areas, including research and conservation. Nevertheless, there are limitations both in hardware and software to extending this methodology to larger buildings. Files grow quickly and the ease of navigation can be affected, especially when stereoscopy and a large screen are used, since it is necessary to calculate more pixels. We firmly believe that new developments in hardware and innovative techniques will soon solve these restrictions.

A hypothetical reconstruction of an archaeological site is also different from an actual copy of it. In a reconstruction, there is a process that culminates with the model and the process itself can be more important than the finished result. In the case of Cacaxtla, the historical research that was carried out to analyze the different stages of construction led to learning about the evolution of the site and the principles of construction, and to a greater understanding of Mesoamerican architects; all this culminated and was synthesized in the building of the 3D models. A reconstruction also lets us visualize the original architectonic spaces, which are usually difficult to grasp from the ruins. In Cacaxtla, it became evident that the site includes many porticoes that limit the opened spaces of the rooms, and that plazas, patios or outer perimeters of the site are surrounded by columns; likewise, the relationship between the buildings is appreciated [7]. The contribution of virtual reality to visualization is unique, since it allows us to experience situations that do not exist. Nevertheless, as was mentioned above, the Cacaxtla model is an idealization of the site, and since this might encourage an excessive use of the imagination or even historical inaccuracies, special care was taken so that the hypotheses were always well founded. In the future, the model should include all the elements that were used to propose the reconstructive solutions. As previously mentioned, Bonampak was made with uniform lighting; Cacaxtla, with one that simulates natural lighting, and Suchilquitongo with both uniform lighting and inner lighting that facilitates a better perception of the reliefs and the depth of the moldings. Although this lighting does not correspond to a simulation of real lighting, it improves the perception of space. Without lighting the reliefs are flat and the depth of the different elements is difficult to understand. Lighting also improves visual quality. Although light and shadow are very interesting on a perceptive level, they create visual distractions when studying the paintings. This is why the possibility of both visualizations is important, to be able to switch from one to the other, depending on specific requirements.

5 Conclusion

A virtual model of an archaeological construction is not only the representation of a site, it is the most complete form of recording archaeological data. To fulfill this function, it must result from a rigorous survey of existing information, a necessary step prior to obtaining useful models to research and document restoration. Teaching based on models of historical architecture benefits from this methodology although its levels of precision are not, in this case, indispensable. Virtual reality is a comprehensive system that can conserve the memory of the world's cultural heritage, supports its conservation and study, and explains and spreads the history of different civilizations.

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